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THE CHOICE OF SUITABLE FREQUENCIES FOR MEASUREMENTS BASED ON FSM

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Vojin Kostić[1], Nebojša Raičević[2], Dragan Kovačević[1]

[1]Electrical Engineering Institute Nikola Tesla, University of Belgrade,
Electric Power Facilities Department, Republic of Serbia
[2]University of Niš, Faculty of Electronic Engineering,
Department of Theoretical Electrical Engineering, Niš, Republic of Serbia

Abstract. *The measurements which are related to the high-voltage substation grounding system are inevitably affected by electromagnetic interference caused by power frequency and its harmonics. In order to avoid the problem due to interferers, traditional measurements are based on heavy test current injection. In most cases this approach is impractical. In this paper, we evaluate experimentally an effective method for eliminating the effect of interference at power frequency. This approach based on test signal at three frequencies, is slightly different from the power frequency. For that matter, there are two problems: 1. How to choose adequate set of test frequencies, and 2. How to determine optimal intensity of the test current. In this paper, we solve the mentioned problems based on the results of extensive field test measurements at substations 110/X kV, 220/X kV and 400/X kV. We show that the set of suitable test frequencies are: 40 Hz, 60 Hz and 75 Hz. Also shown is a method for finding the optimal intensity of the test current.*

Key words: *grounding system, electromagnetic interference, spectral analysis*

1. INTRODUCTION

The performance metrics of the substation grounding system should be periodically tested. In order to obtain the corresponding results (at fundamental power frequency), measurements are commonly performed at power frequency, i.e. at 50 Hz. To avoid interruption of service during the test, the high-voltage substation must be energized. For that matter, through the substation's grounding grid there flows composite current. Composite current is a combination of the current at fundamental frequency and the

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Corresponding author: Vojin I. Kostić
Electrical Engineering Institute Nikola Tesla, University of Belgrade, Koste Glavinića 8a, 11000 Belgrade, Republic of Serbia
E-mail: vojin@ieent.org

current at power frequency harmonics. In order to ensure necessary signal-to-interference ratio (e.g., 30 dB), the intensity of the corresponding test current must be large (typically, in the range of 50 to 100 A for measurement impedance of grounding system [1] - [2], and in the range of 100 to 200 A for measurement touch and step voltages [3]). However, in the most practical cases, very large test current can be impractical**.**

An alternative approach, *Frequency Shift Method* (FSM), (see [4] - [7]) use the test current at frequencies (at least three frequencies, f_{ti}, i=1, 2 and 3) which are slightly different from the fundamental power frequency. Afterwards, using linear regression on the measured results at f_{ti}, the grounding system impedance, the touch voltage or step voltage one can predict is at 50 Hz. In this case, the interference at 50 Hz is not a problem. Herein, generally, the problem is only related to the level of the background noise floor. Fortunately, the noise floor is significantly lower than the interference level. Therefore, in the sequel, we will take account only signal-to-noise ratio (SNR). The bandpass filter is used in order to select the test signal at frequency, f_{ti}. In this way, we achieve the requered SNR (i.e., the SNR sufficient for a reliable measurement of the performance metric of the grounding system).

Therefore, the prerequisite for the application of FSM, is to find the response to two questions: 1. how can we choose $f_{ti,}$ and 2. how much must be the intensity of the test current at frequency $f_{ti.}$ that guarantees sufficient SNR (say, SNR=30 dB)?

Certainly, there are some practical limitations that influence responses to the above mentioned questions. Namely, there are coupling limitations and filtration limitations. On one hand, coupling effects between the test leads limit the upper test frequency to less than 80 Hz. On the other hand, the practical filtration limitations are related to the value of the ratio f_{ti}/50 Hz (or 50 Hz/f_{ti}). In fact, the value of the ratio f_{ti}/50 Hz (or 50 Hz/f_{ti}) affects the choice of filter type and order of the filter. Namely, this ratio affects the complexity of the bandpass filter. Determination of optimal intensity for the test current at test frequency f_{ti} will be explained in Section 3.

When we inject test current at the frequency f_{ti} in the grounding system, then appear new spectral components due to mixing f_{ti}, fundamental power frequency, and harmonic frequencies. In order to solve the above mentioned problem, for this very complex scenario, we conduct field experiments at ten high-voltage substations (six of them were 110/X kV, two 220/X kV and two 400/X kV).

The remainder of this paper is organized as follows. Section 2 describes the methodology that we follow throughout our experiments. In Section 3, detailed discussion of the test results is presented. Section 4 briefly summarizes the results and draws relevant conclusions.

2. PRINCIPLES OF MEASUREMENT

This section attempts to give a quick glance at the signal processing technique used in the experiment. The measurement setup is depicted in Fig.1. The digital oscilloscope collects the composite signal in the time-domain. The composite signal is time-varying since it is caused by sum of current due to the test current and the residual current usually present in the grounding grid (unbalance current). The composite signal will be post-processed by DFT (Digital Fourier Transform) [8].

The DFT is a useful analytical tool that has been applied for phasor measurement and harmonic analysis. DFT transforms the signal from time-domain to the frequency-domain. The basic equation that describes the DFT is

$$S(k) = \frac{1}{N}\sum_{n=0}^{N-1} s(n)e^{-j\omega_k n} \tag{1}$$

where $S(k)$ is the DFT evaluated at the frequency ω_k, N is the window length, $\omega_k = 2k\pi/N$ is a set of fixed and equally spaced frequencies, $0 \le k \le N - 1$. The fast Fourier transform (FFT) is the DFT's computational efficient implementation. With this tool, it is possible to have an estimation of the fundamental amplitude and its harmonics with a reasonable approximation. FFT performs well for estimation of periodic signals in a stationary state. The results of the estimation can be improved with windowing, e.g. by Hamming, Hanning, Blackman or Kaiser window. If the longer the data window (N), the better frequency resolution is achieved. In this work, we used Hamming window.

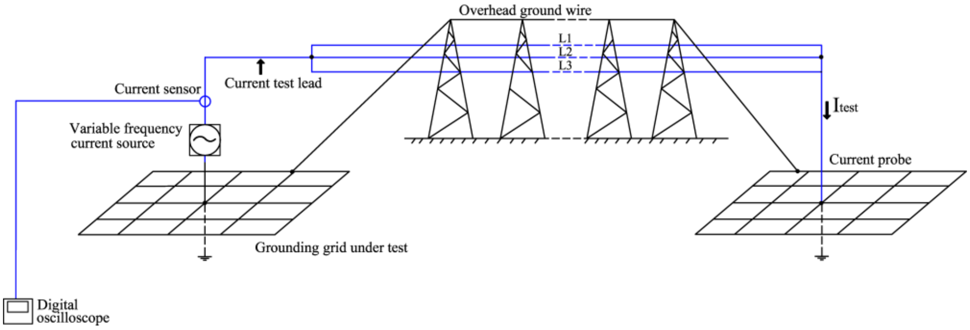


Fig. 1 Measurement setup

According to the limitations mentioned in the introductory section, our measurement is band limited. In fact, we consider spectral amplitudes in the frequency band between 30 and 80 Hz. Next, based on preliminary considerations, we select: $f_{t1} \hat{=} f_1$=40 Hz, $f_{t2} \hat{=} f_2$=60 Hz and $f_{t3} \hat{=} f_3$=75 Hz as a potentially suitable set of test frequencies. The frequencies are generated by variable frequency power source (California Instruments, type 15001iM). In the experiments, intentionally we use different values of I_{test}.

The composite signal was recorded during a time window of 1 s. Hence, frequency resolution is 1 Hz.

3. RESULTS AND DISCUSSION

The measurements were conducted at ten high-voltage substations (six of them were 110/X kV, two 220/X kV and two 400/X kV). During the experiment, the substation was in normal operating condition. According to the experiments that follow procedures described in Section 2, we present spectral results as depicted in Fig. 2 (a) ($f_i = f_1$=40 Hz), Fig. 2 (b) ($f_i = f_2$=60 Hz) and Fig. 2 (c) ($f_i = f_3$=75 Hz). Each figure ((a), (b) and (c)) contains 10 subplots. The first six subplots (from top to bottom) correspond to substations rating 110/X kV. Next two subplots correspond to the substations rating 220/X kV. The last two subplots correspond to substations rating 400/X kV. The test current, I_{test}, which is used in the respective experiment is written down in the subplot.

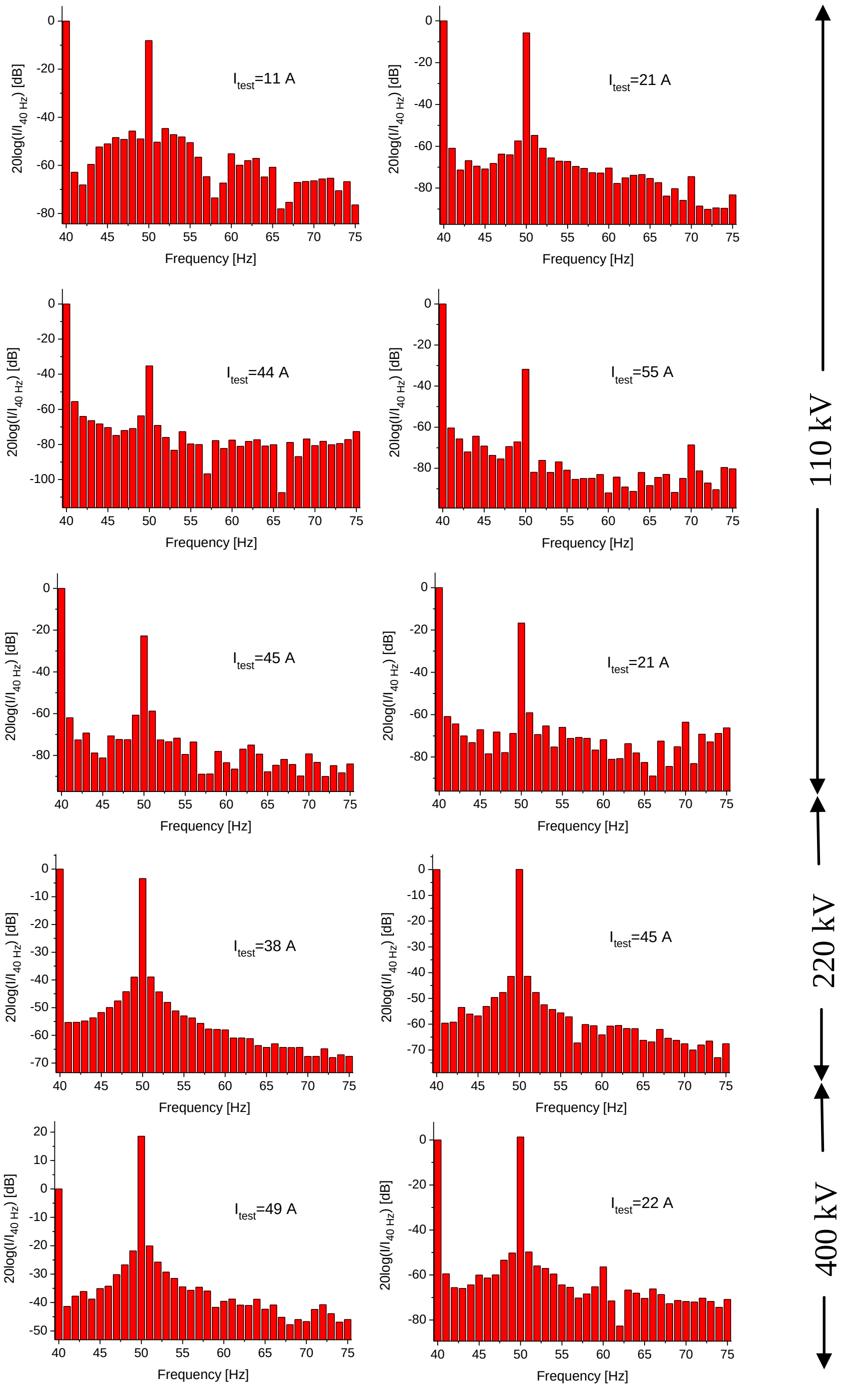
The waveform of the composite signal has a time-varying envelope. This is due to the fact that the composite signal, $z(t)$, is

$$z(t) = s_f(t) + s_t(t) + i(t) \tag{2}$$

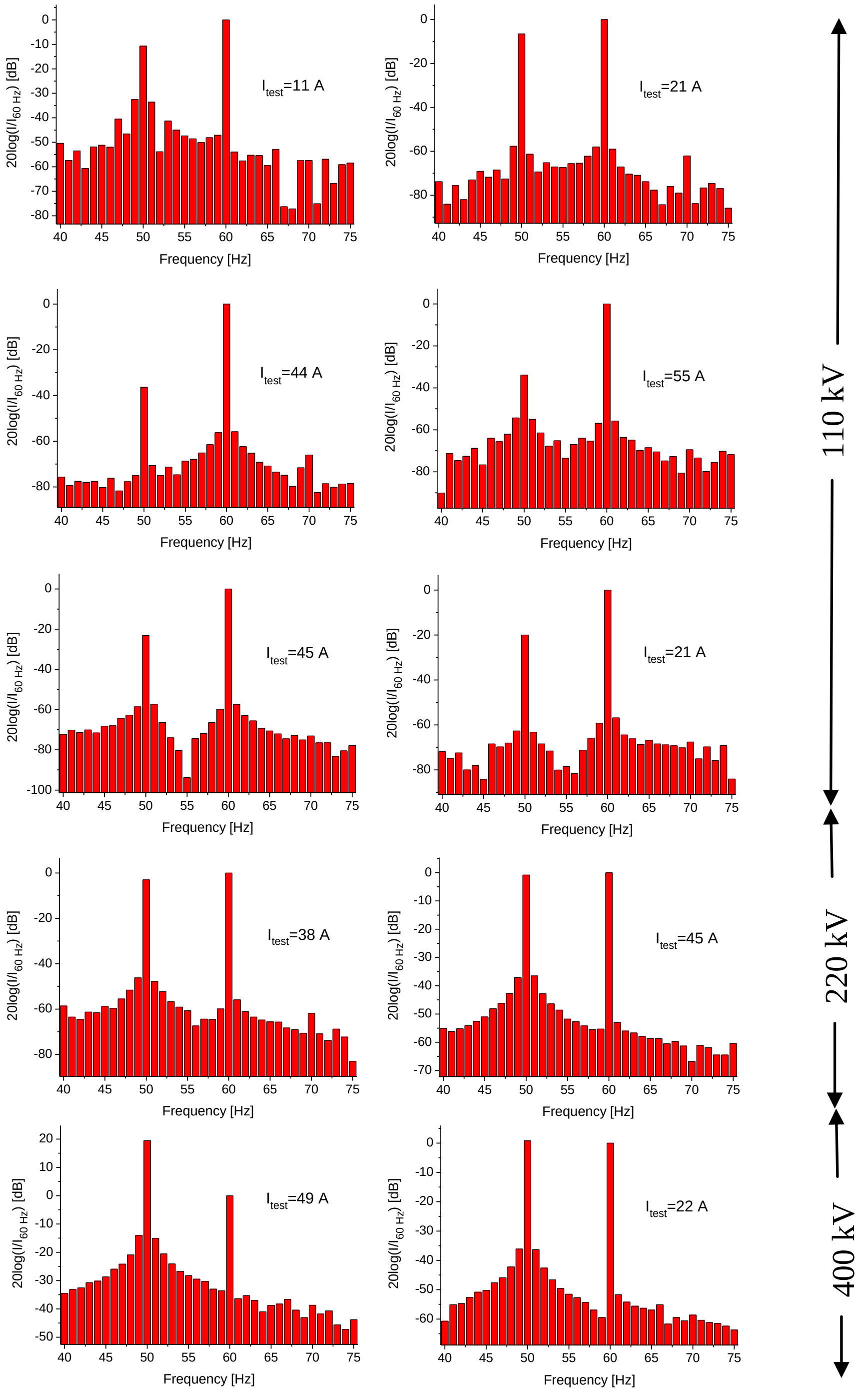
where $s_f(t)$ is the signal at the fundamental frequency, $s_t(t)$ is the test signal at frequency f_{ti}, and $i(t)$ is the waveform caused by power frequency harmonics. The depth of amplitude modulation depends of the ratio of residual current at f_f (=50 Hz) and the test current at frequency f_{ti} (since $s_f(t)$ is proportional to residual current at f_f, similarly, $s_t(t)$ is proportional to test current at f_{ti}). The envelope of $z(t)$ fluctuates according to beat frequency, $f_b \hat{=} | f_f - f_{ti} |$, where f_f=50 Hz and f_{ti} is the test frequency (40, 60 or 75 Hz). Evidently, the time-domain representation of the composite signal does not provide a useful insight into the relationship between composite signal components. Therefore, the spectral analysis of $z(t)$ is necessary.

As we see from Fig. 2, the dominant spectral components of the composite signal $z(t)$ are at f_f and f_{ti} (the level of spectral amplitudes is normalized to the level of spectral amplitude at frequency f_{ti} and expressed in dB). It is important to note that, in the observed bandwidth, there are no other discrete spectral components. Generally, the noise floor is about 40 to 60 dB below the spectral component at f_f regardless of voltage rating of substation.

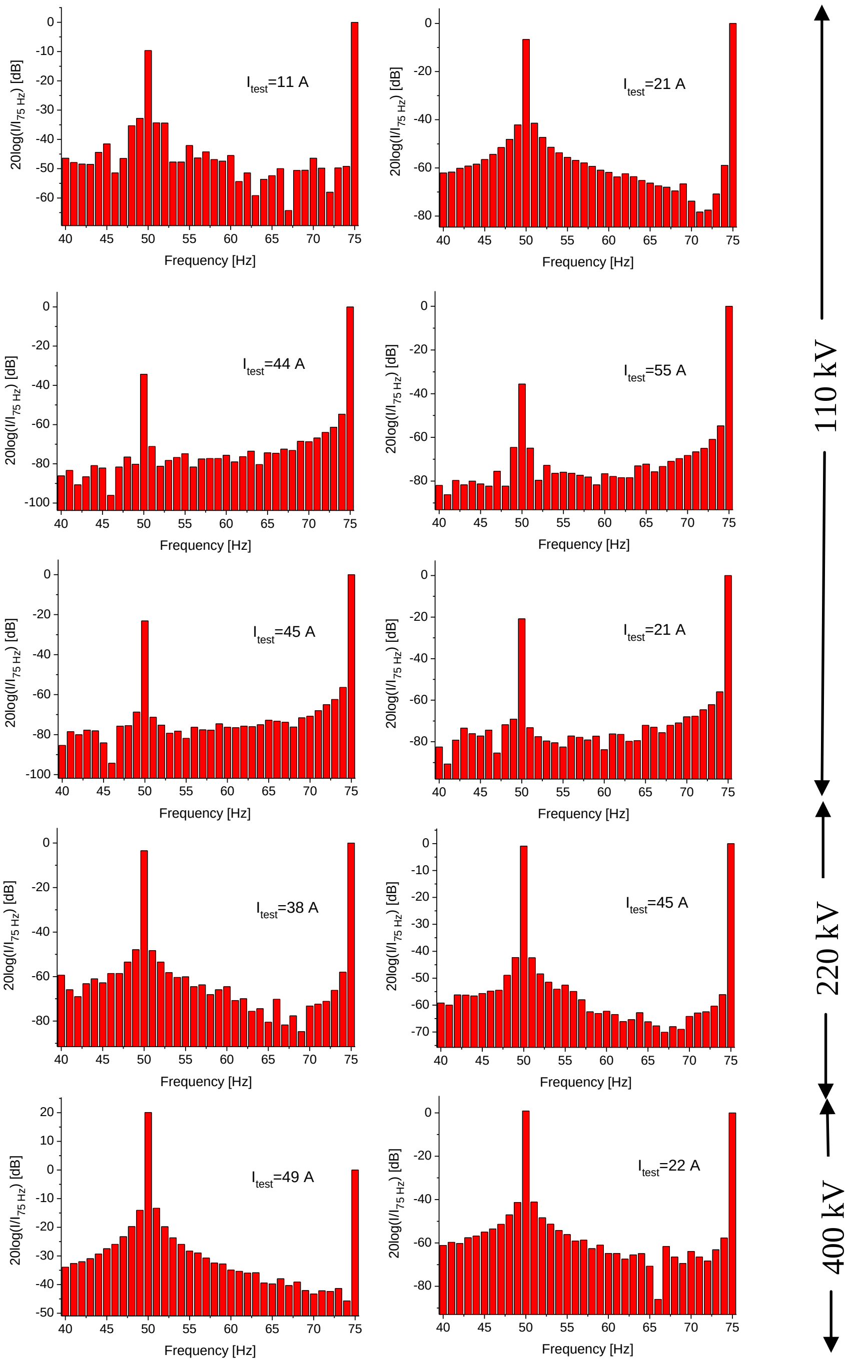
The level of spectral amplitude at f_{ti} depends of I_{test}. Consequently, the SNR at the test frequency depends of I_{test}. For example, see Fig 2 (a), row 5- left, I_{test}=49 A, the signal-to-noise ratio (at 40 Hz) is about 40 dB. Quite differently, from Fig 2 (a), row 5-right, I_{test}=22 A, one can find that the signal-to-noise ratio is about 60 dB. These examples clearly show that one should be careful when choosing I_{test} for purposes of FSM. Namely, at each test frequency, f_i, it is sufficient to be SNR=30 dB. Two factors are responsible for the realization of the above request: filtration and intensity of the test current. The bandpass filter should be able to extract f_{ti} and to suppress the amplitude at f_f=50 Hz. The noise floor around f_{ti} is practically constant. Hence, the SNR depends only on I_{test}. Thus, before a specific measurement based on FSM (e.g., measurement of the grounding system impedance or measurement of touch and step voltage) should be implemented into the experiment with the test current, e.g., of 10 A. The corresponding spectral diagrams for three test frequencies should be recorded. Afterward, the SNR should be examined at each test frequency. If the SNR is greater than 30dB (which is usually the case), by simple calculation, one can reduce the intensity of the test current to the optimal value. Accordingly, for the above mentioned cases (Fig. 2 (a), row 5- left, I_{test}=49 A, and row 5- right, I_{test}=22 A), it is easy to obtain optimal value of test current, 15.5A and 0.7A, respectively.


I_test=11 A
I_test=21 A
I_test=44 A
I_test=55 A
I_test=45 A
I_test=21 A
I_test=38 A
I_test=45 A
I_test=49 A
I_test=22 A
20log(I/I_40 Hz) [dB]
Frequency [Hz]
40
45
50
55
60
65
70
75
110 kV
220 kV
400 kV

(a)


I_test=11 A
I_test=21 A
I_test=44 A
I_test=55 A
I_test=45 A
I_test=21 A
I_test=38 A
I_test=45 A
I_test=49 A
I_test=22 A
20log(I/I_60 Hz) [dB]
Frequency [Hz]
110 kV
220 kV
400 kV

(b)



(c)

Fig. 2 Spectral diagrams, (a) f_1=40 Hz, (b) f_2=60 Hz, (c) f_3=75 Hz

In post-processing, the proposed test frequencies allow relatively easy filtering. Namely, for the purposes of selecting the test signal at f_1, f_2 or f_3, the corresponding digital bandpass filter can be easily implemented. Its bandwidth must be limited to a value slightly larger than the expected frequency instability of both power frequency and frequency of the test signal source. Therefore, it is preferable that the filter has a bandwidth of about 3 Hz. We used Butterworth type of filter (order: 12*th* for central frequency 40 Hz, 10*th* for central frequency 60 Hz, and 8*th* for central frequency 75 Hz,). Accordingly, the choice of test frequencies (40, 60 and 75 Hz) is adequate and practical. Otherwise, if the test frequency is closer to 50 Hz, there would be a serious problem in terms of filtering.

6. CONCLUSION

Major findings of this paper are summarized below:

1. Based on the detailed analysis of experimental results carried out in very different high-voltage substations, we elaborated an optimal set of test frequencies suitable for FSM. The frequencies are: 40 Hz, 60 Hz and 75 Hz.
2. Quite different from the conventional method for suppression of power frequency interference (where the experimenter follows a very conservative recommendation for test current intensity), in the FSM based test, the experimenter can always use a specific optimal intensity of the test current.
3. We point out, that the proposed test frequencies have been successfully used for FSM based measurements of grounding system impedance [4 - 6], as well as for FSM based testing of touch and step voltages [7].

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