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Evaluation of Non-failure Operation Time of Power System Elements in Virtual Test Bed Environment via Time-Frequency Analysis

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Abstract *– A new methodology for the evaluation of non-failure operating time (NFOT) in Virtual Test Bed Environment is proposed. The proposed method is featured by the application of signal processing techniques to estimate parameters of reliability at the earliest steps of design based on intercoupling 1/f noise and reliability of power system elements. The proposed approach enables one to directly quantify the reliability of the system by the investigation of the physical properties of the nonequilibrium fluctuation.*

Keywords *– Nonequilibrium fluctuations, 1/f noise, circuit simulation, time-frequency analysis, hardware's reliability*

I. INTRODUCTION

The lifetime forecasting of an electric power system including the estimation of stability's of future products is extremely desirable, particularly at the beginning of design of overall systems. However, it is hard to establish lifetime forecasting strategy based on knowledge of the circuitry only. Unfortunately, the testing of pilot models is very expensive, and it is difficult realizable on early stages of design. However, the intensity of devices failure (the value, inverse mean time of no-failure operation) and intensity of 1/f-noise of those devices are interconnected [1-5]. However it is impossible to utilize this fundamental theory of physics in design calculations. Because the intensities of surplus noises with 1/f spectrum cannot be obtained without experiments. Hence, in this paper, we discuss a signal processing based methodology to evaluate non-failure operating time (NFOT).

The proposed approach is based on the spectral characteristics of the intercoupling 1/f noise and reliability of an element. We have developed the technique for estimation of element reliability, in particularly non-failure-operating time basing on the assumption that 1/f noise is non-equilibrium fluctuations of reactive energy, i.e. energies of electric and magnetic fields in the materials of elements [6, 7]. Squared voltage (or current) of noise is measured on the output of tunable bandpass filter in experiments. If the equilibrium noises are investigated, then the result will be equal to resistive power [8]. In the case for non-equilibrium 1/*f* noises, we will assume the result is some value, which is proportional to reactive energy ($W_E=CV^2/2$; $W_M=LI^2/2$) [6, 7]. Hence, one can find that the minimal frequency, when the hits of fluctuating energies exceed the breaking energies in materials. It is a notable fact that very slow growths of reactive energy are transforming in slow growth of energies of stress in materials. The minimal frequency is inversely operating time of a device that allows to calculate NFOT. It is clear that all mentioned ideas and approached are strongly connected with frequency characteristics of a device.

However, different frequency parameters and characteristics are necessary for the estimations as mentioned above. Any parameters of the signal as response of a circuit, which allow one to detect time-varying frequency properties of a circuit, will be useful for the estimation of the NFOT. Hence, in this paper, we utilize an advance signal processing technique, i.e., the time-frequency analysis in order to specify time-varying 1/f noise signature and to find important frequency properties for NFOT estimations.

II. NON-FAILURE OPERATION TIME OF ELEMENTS

In this section, the method for calculation of 1/f noise intensity is discussed. The Fig. 1 is illustrated the typical noise spectrum of any electronic device. 1/f noise $(G/f)^n$ become dominating over thermal noise $4kT_{Ns}R$ on the frequencies less than f_{th}.

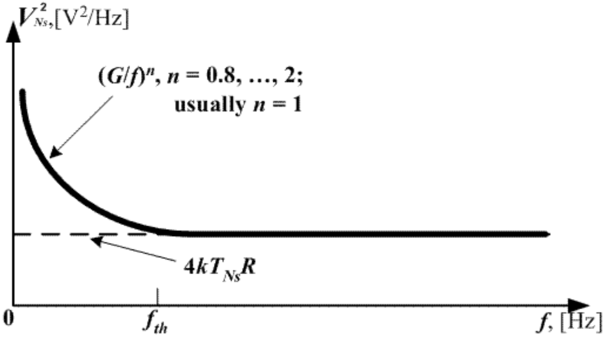

Fig.1. Typical noise spectrum of an electronic device.

A diagram in Fig. 1 is the typical noise spectrum, when squared voltage is measured. If we replaceV^2_{Ns} on W_E (W_M),

the response will not change, but the constant G will have different unit: watt*second/second = watt and different meaning. Hence, thermal noise level will be kT (watt-sec.). So, we can define the constant $G^n = kT_{Ns}f_{th}^n$. Thus, frequency dependence of reactive energy fluctuations is $kT_{Ns}(f_{th}/f)^n$. One can calculate this dependence in logarithmic scale as follows:
$10lg(kT_{Ns}(f_{th}/f)^n/kT_{Ns0}) = 10lg(T_{Ns}/T_{Ns0})+n10lg(f_{th}/f)$,
where $T_{Ns0} = 300$ [K] – temperature for normal conditions.

Energetic approach allows one to illustrate the noise spectrum in logarithmic scale as shown in Fig. 2. Thermal noise energy and 1/f noise energy are equally for $f = f_{th}$: $(G/f_{th})^n = kT_{Ns}$. In Fig. 2, the levels of thermal noise kT_{Nsi} (i = 0, 1, 2) and levels of breaking energies W_{Brj} (j = 1, 2) are provided as a logarithmic function of frequency. Note that the variation of the level in thermal noise is independent of the threshold frequency f_{th}. The cross point of two lines (1/f noise with level of breaking energy W_{Brk}) determines the minimal frequency, which is inversely proportional to NFOT. Moving thermal noise line move up/down 1/f noise line that is changing the position of a cross point. For instance, moving up thermal noise lineally increases f_{th}, i.e. decreasing NFOT. If the order n is increasing, NFOT will also decrease. Notes: frequency $2{,}8\cdot10^{-4}$Hz has period 1 hour; $1{,}16\cdot10^{-5}$ Hz – 24 hours; $3.86\cdot10^{-7}$ Hz – a month; $3{,}2\cdot10^{-8}$ Hz – a year.

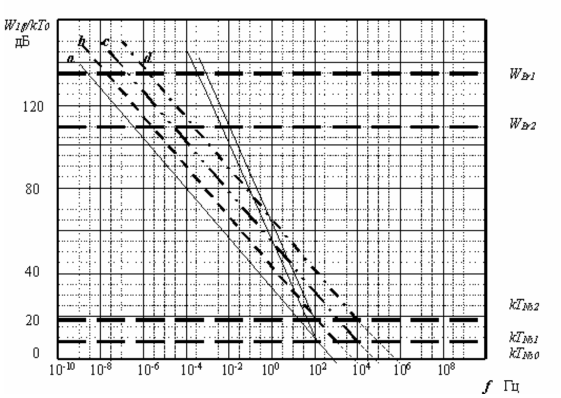

Fig.2. The spectrums for different value n.

As discussed above, it is necessary to determine the constant G for reliability estimations. This constant cannot be measured, in the earliest steps of design. Therefore, we have suggested an empirical formula for numerical evaluation of G:

$$G = K_P P(\Delta f/f_0)(\Delta T/T). \qquad (1)$$

where P – dissipative power (Wt); f_0 – medium frequency (Hz) of a device presented frequency filter; Δf – passband of the “filter”; T – average temperature during operating time; . $\Delta T = T - T_0$ – overheating device and T_0 – environment temperature. K_P = 10e-10 – empirical coefficient. However, it is necessary to determine the variables of P, Δf, f_0, ΔT and T so that they are calculated by method described in next section.

III. VTB SIMULATION SETUP

The methodology described above is the theoretical basis of estimator of the Overheat and Reliability Estimation Tool (OHR) implemented in the Virtual Test Bed (VTB) that is [9]. The algorithmic structure of the chart of estimator is depicted in Fig. 3.

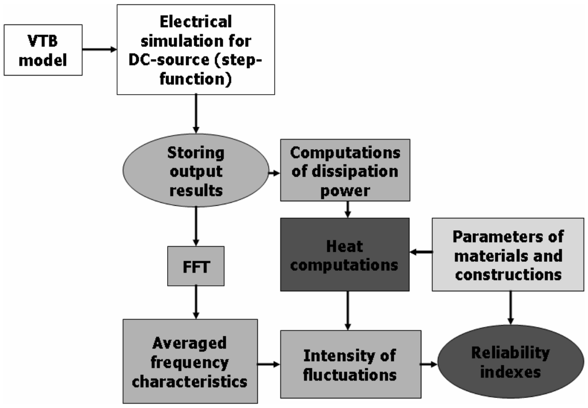

Fig. 3. Estimation Procedure of NFOT in VTB environment.

The input signal for the circuit should be single impulse with duration more than transient time. This requirement is conditioned by the procedures in OHR tool. The corresponding responses of the circuit are stored in buffer for following processing stage. Then, the OHR is computing dissipative power and frequency characteristic of the output signal time series.

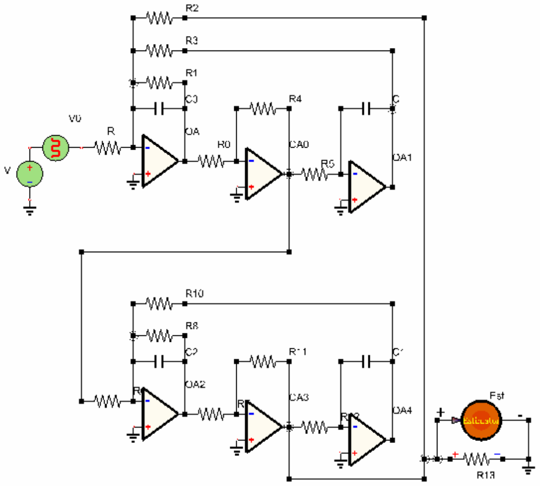

Fig. 4. VTB circuit setup.

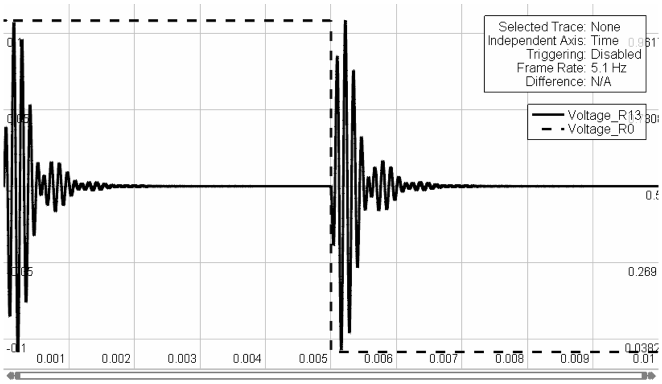

Fig. 5. Input and output time series obtained by VTB simulation.

OHR detects dominating bandpass frequency components in order to determine 1/f noise and parameters of frequency characteristic. The results of heat computations and frequency analysis allow to one find intensity of non-equilibrium fluctuations. The highest possible value of non-failure operating time and other indexes of reliability are estimated by the intensity of fluctuations and breaking energies for materials.

III. VTB SIMULATION RESULTS

Utilizing the features of the VTB-model for the operational amplifiers uA747C, one can simulate the estimation of non-failure operating time of an ARC-filter, which is composed of two operational amplifiers (OA), a PCB board has sizes 50x50x5 mm^3. You could see the equivalent circuit of the ARC-filter in the small-signal operation in Fig. 4. The circuit schematics provided in Fig. 4 is utilized for the computing pulse response, which is necessary for calculating frequency parameters $\Delta f/f_0$ in the formula (*) and intensity of non-equilibrium fluctuation. Specific voltage sources (DC and impulse voltage source) are connected with input terminals for obtaining pulse response. The Estimator is connected to output terminals as voltmeter. PCB configuration is assumed parallelepiped form with sizes 50x50x5 mm^3 and emissivity factor equals 0.1 that is necessary for overheat calculation $\Delta T/T$ in the (1).

Hence we intoduce time-frequency analysis for the post-processing of the output time series obtained by the simulation. The time-frequency distribution is kind of energy distribution so that the first pulse is dominating on time-frequency plane. The frequency spectrum located in bottom left corresponds to the marginal of the time-frequency distribution in frequency domain. In the time-frequency distribution provided in Fig. 6, one can keep tract of the time-varying frequency components of the pulses in terms of time and frequency in joint manner.

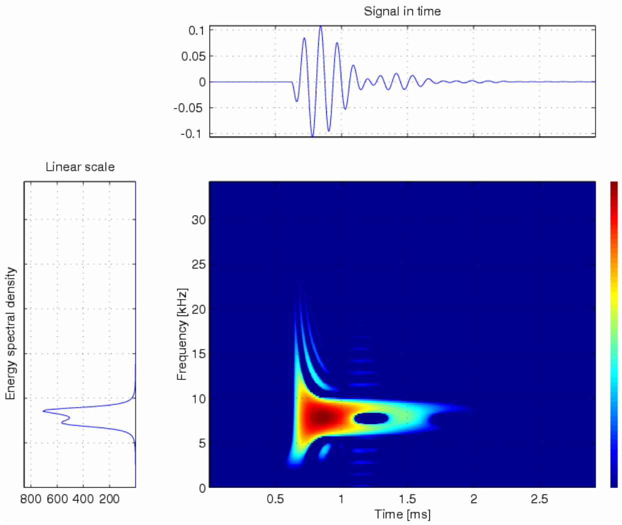

Fig. 6. Time-frequency distribution of the time series data provided in Fig. 5.

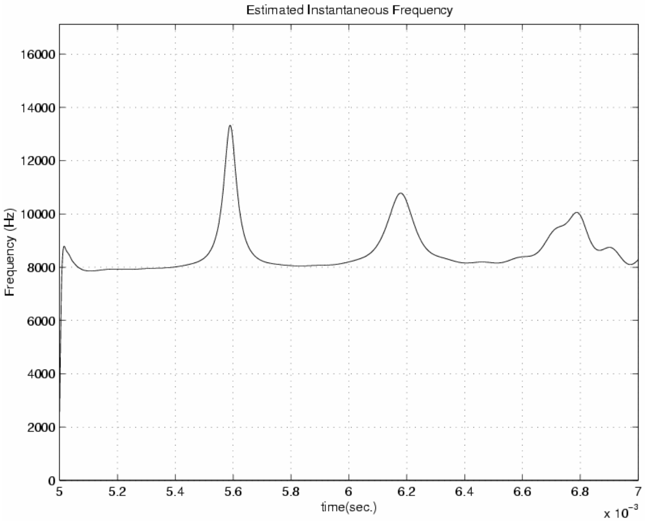

Fig. 7. Instantaneous frequency estimation of the time series provided in Fig. 5.

Based on the time-frequency distribution of the signal, one can calculate instantaneous frequency of the time series from the time-frequency distribution obtained below. The instantaneous frequency is a selection of the most representative frequency components at a given time of interest in associated with normalized manner, which implies that we can see the variation of the frequency contents as a function of time even at the time instance where signal energy is relatively low.

The calculated instantaneous frequency is provided in Fig. 7. The parts of the first pulse (5ms.~5.5 ms.) and second pulse (5.7ms.~6.0ms.) show 8 kHz instantaneous frequency. However, at 5.6 ms. and 6.2 ms., the instantaneous frequency abruptly increases in instantaneous frequency correspond to the time instances of the phase shifts in time domain in Fig. 5.

In this paper, we utilize the time varying instantaneous frequency of the output time series in order to obtain the frequency characteristic and detecting medium frequency and pass band. The medium frequency is 8 kHz (fig.6, fig.7). The simplest way to detect passband is using the diagram of energy spectrum density (fig.6, left diagram) for the level 0.707. The preliminary results of overheat estimations (voltage of power supply for operational amplifier: ±5V, ±10V, ±15V) are presented in the TABLE I.

TABLE I
Estimations of NFOT for ARC-filter.

Power Supply, Volts	Dissipative power, mW	Overheat, uK	NFOT, hours
10	84	6.6	35600
20	168	13	8900
30	252	20	3900

In the real life problems, this time will be smaller, because of different technological defects. The dependence of NFOT from several factors (circuitry, design, and consumption power) is more important than estimated values at the earliest steps of development.

IV. PRELIMINARY DISCUSSION

Fluctuations of reactive power (derivative of reactive energy) have to have frequency independent spectrum, when the energy spectrum inversely proportional to frequency. It means that harmonic function for any spectrum component of reactive energy fluctuations intersects zero level with equal incidence. In other words, maximal rate of reactive energy changing is the same for any frequency.

The Fig. 8 shows that new harmonics are generated during the operating time, which ones have decreasing frequencies and increasing amplitudes. According to the discussion we can guess spectrum of the response (left bottom side in Fig. 6) has new frequency components, which ones are not directly connected with time diagram (right top side in Fig. 6) as determinate function. Certainly, these new frequencies are correlated with nonequilibrium fluctuations of reactive energy. The time-frequency analysis allows revealing the implicit frequencies that can help to get low-frequency components and improve a reliability of NFOT algorithm.

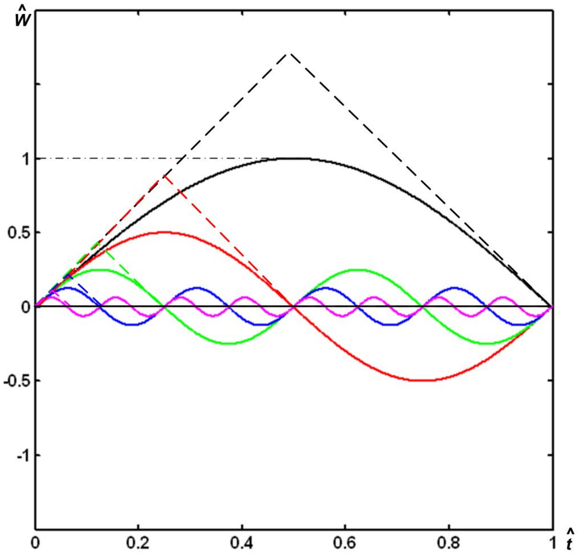

Fig. 8. Interpretation of the reactive energy spectrum in the time-domain.

V. CONCLUSION

Thus, the methodology of reliability estimation by 1/f noise level is presented. The way to apply one in VTB is shown. Of course, the question about verification of the results is reasonable. The best way to check it is comparison our results with reliability data for known devices. We were making estimations for different elements (e.g. resistors, transistors, chips, etc.) for normal working conditions. The obtained results differ from device specification within the limits of one order in the worst case. But the best application for provided method is choice optimal variant of a solution by reliability criterion at the earliest steps of design. It is also possible to research a dependence of NFOT from several factors like circuitry, design, consumption power. We believe it is more important than accuracy of the estimations.

ACKNOWLEDEMENT

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