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Obtaining frequency response of automatic voltage regulators and power system stabilizers in closed loop system using *Real Time Digital Simulator*

Method of obtaining frequency responses of automatic voltage regulators (AVR) and power system stabilizers (PSS) in close loop system using RTDS is proposing. Approbation of method and assessment of accuracy of obtained frequency responses was performed. Capability of using RTDS for verification of AVR and PSS mathematical models was shown.

References:

MATHEMATICAL MODEL, PHYSICAL MODEL, AUTOMATIC VOLTAGE REGULATOR, POWER SYSTEM STABILIZER, AVR, PSS, FREQUENCY RESPONSE, VERIFICATION, REAL TIME DIGITAL SIMULATION, RTDS

I. Introduction

About 15 years ago in Russian Unified Power System replacement of old analog automation equipment with modern digital technologies has been started. During that period of time many Russian Power stations were equipped with AVRs and PSSs of foreign and Russian manufacturers. Wide variety of algorithms and hardware used by different companies urged System Operator to create standard which define requirements for AVRs and PSSs. According to this standard, AVR and PSS, which are to be installed on power station, must pass all tests of prescribed program. If AVR/PSS successfully pass all tests, it receive certificate. Presently this program is performed on «STC UPS» JSC physical model.

One of the directions of work which are performed in «STC UPS» JSC is testing AVRs and PSSs full-scale specimens and studying impact of their work on power system performance during electromechanical transients. Such researches have been performed in «STC UPS» JSC since year 2002 [1]. Among these researches two main directions can be distinguished:

1. AVRs and PSSs certification
2. Adjustment of AVRs and PSSs coefficients for specific power system schemes and specific regimes.

First direction include following steps:

1. Performing certification program tests (if AVR/PSS successfully pass all tests, it means that it possess experimentally approved ability to work correctly in complex and widely varying power systems schemes)

2. Creating a verified mathematical model of AVR and PSS. Creating mathematical model and its verification is performed based on structural schemes and frequency responses, which are provided by manufacturer. Subsequently the model can be used in software, like Eurostag [2].

Second direction of researches (adjustment of AVRs and PSS coefficients) begins with calculations of electromechanical transients in Eurostag software. Based on calculations results proper coefficients are chosen. It is obvious that calculation results depend on adequacy of power system elements mathematical models implemented in Eurostag software.

After AVRs and PSSs coefficients have been chosen, they are examined on physical model. To create a physical model of Power System it is often needed to implement various algorithms in control systems of one or more generators. Initially physical model was not designed for that. To overcome this problem in 2012 "Regulator" software-hardware system was created [3]. "Regulator" is a system which allows creating and implementing digital models of AVRs, PSSs and speed governing systems. In the same year "Regulator" was tested and verified with a help of RTDS Simulator [4].

As shown above, verification of AVRs mathematical models is very important problem. Those models are used for calculations in Eurostag software, RTDS Simulator as well as for performing researches on physical model(within "Regulator" software-hardware system).

II. Problem overview

As it was said, presently verification of AVRs and PSSs mathematical models is performed based on data provided by manufacturer (structural schemes and frequency responses). «STC UPS» JSC is interested in creating of method which will allow verifying this data. Verification of AVRs and PSSs mathematical models is performed by comparing frequency responses of full-scaled specimen with frequency responses of corresponding mathematical models. Hence it is necessary to create method of obtaining frequency responses of AVRs and PSSs experimentally.

From classic control theory point of view any modern AVR and PSS can be represented as multiple input single output system (MISO system). If we disable all inputs in MISO system except one, it becomes SISO system. Frequency response of SISO system is a measure of magnitude and phase of the output as a function of frequency, in comparison to the input. As an example let us take PPS2B structure scheme. PSS2B has to inputs: Power input and Shaft speed input. Hence, two frequency responses could be obtained.

Usually for measuring frequency responses of SISO liner time-irrelevant system following methods are applied:

1. Sending on input of SISO system impulse (Dirac delta function) and measuring its response
2. Applying a signal with a wide frequency spectrum
3. Sending a constant-amplitude pure tone through the bandwidth of interest and measuring the output level and phase shift relative to the input

First two methods can’t be applied because of limiters, which can’t be disabled in full-scale specimens of AVRs and PSSs. So, third method was chosen. But even in this case number of problems appears during obtaining frequency responses:

1. Input signals of AVR are instantaneous currents and voltages
2. Most AVRs can't work without feedback signals
3. Some AVRs doesn't measure input parameters directly, instead of that those parameters are calculated from other signals(i.e. field current is calculated from instantaneous currents, which are measured before rectifier)
4. PSS can’t work without AVR

To overcome those problems it was suggested to obtain AVRs and PSSs frequency responses during it works in normal operational mode in closed-loop system (AVR regulate synchronous generator terminal voltage). By authors of this article method was developed, using RTDS Simulator, personal computer with ADC/DAC card installed and special software "FreqChar".

III. Method description

Within RTDS simple power system “Generator-Line-Bus” was implemented. This scheme has following distinguishing features

1. Generator model with shaft speed input signals is used.
2. Generator model doesn’t have saturation.
3. AC Type – CC Control SRC model was used
4. Line is represented as L/R element

Required for specific model of AVR signals (instantaneous currents and voltages) are sent from simulation to GTAO card. GTAO output signals are sent to amplifiers, and amplifier output signals go to AVR. AVRs six digital signals are sent to GTDI. If automatic regulator has analog output signal, it could be sent to GTAI card, and model of Firing Pulse Generator is used in this case. After AVR has been connected to RTDS, simulation begins. During simulation, AVR works in closed-loop system, in its normal operational mode.

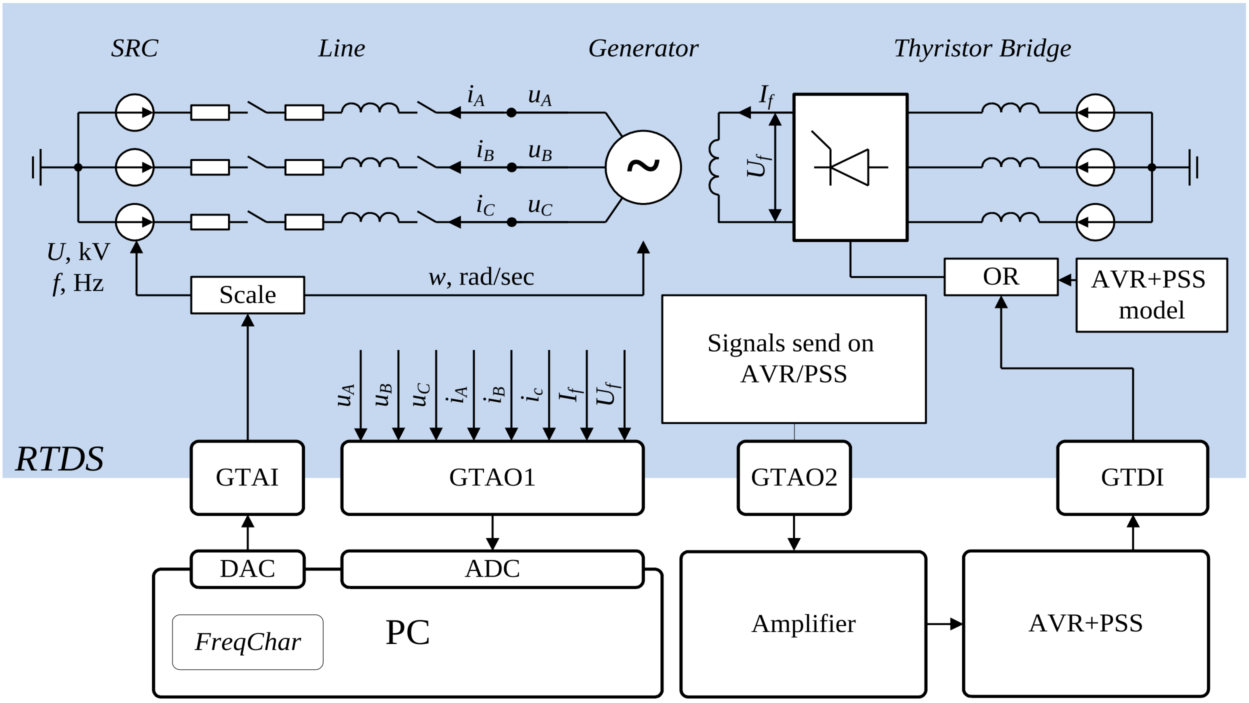


Fig. 1 Scheme for obtaining frequency responses of AVR/PSS using RTDS Simulator

For obtaining the frequency responses of AVR and PSS, developed in «STC UPS» JSC software "FreqChar" is used. "FreqChar" is installed on PC with ADC/DAC, it generate sinusoidal signal of f_m frequency and send it to DAC. From DAC signal goes to GTAI card. Within RTDS signal could be scaled and sent to following inputs

1. Frequency SRC input
2. Voltage SRC input
3. Generator shaft speed input

Thereby bus voltage RMS, bus voltage frequency and shaft speed could be modulated. If voltage frequency is modulated, than at the same time modulation signal should be sent on shaft speed input due to maintain generator load angle.

Modern AVRs and PPSs can include following inputs:

1. Generator terminal voltage input
2. Voltage frequency input
3. Active power input
4. Shaft speed input
5. Field current input

As an example, obtaining the frequency response of PI voltage regulator will be considered. All inputs of AVR, except terminal voltage input are disabled. Then "FreqChar" send modulation signal, during time set by user. In power system parameters oscillations of f_m frequency appear. "FreqChar" software writes following parameters

1. Three instantaneous terminal voltages (ua, ub, uc)
2. Three instantaneous currents (ia, ib, ic)
3. Field current (If)
4. Field voltage (Uf)

5. Shaft speed (w)

By definition frequency response is a measure of magnitude and phase of the output as a function of frequency, in comparison to the input. “FreqChar” software calculates RMS terminal voltage, from written data (three instantaneous terminal voltages) and derive main harmonic by representation it as a Fourier series. After that it saves magnitude and phase of this harmonic. At the same way “FreqChar” determine magnitude and phase of main harmonic of field voltage. One point of frequency response is obtained by calculation of quotient of harmonics magnitudes and difference of its phases. We make an assumption, that phase of derived main harmonic of field voltage is equal to phase of AVR output signal. And amplitude of derived main harmonic of field voltage is equal to amplitude of AVR output signal, multiplied by constant coefficient.

Approbation of the method showed that this assumption is valid. To obtain the rest points of frequency response experiment should be repeated with another modulation frequency.

Sometimes it is impossible to disable one or more inputs. For example PI voltage regulator must always be at work. In this case there could be two different cases. (Fig. 2 and Fig. 3)

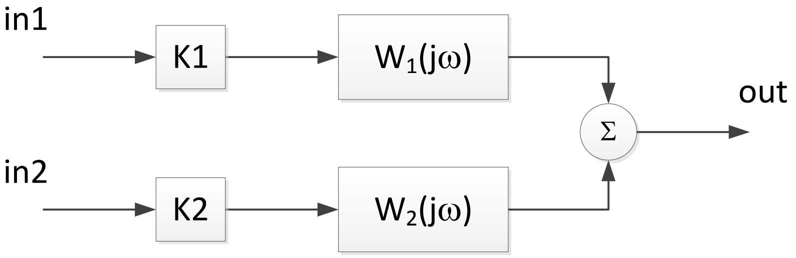


Fig. 2 Two parallel regulation paths

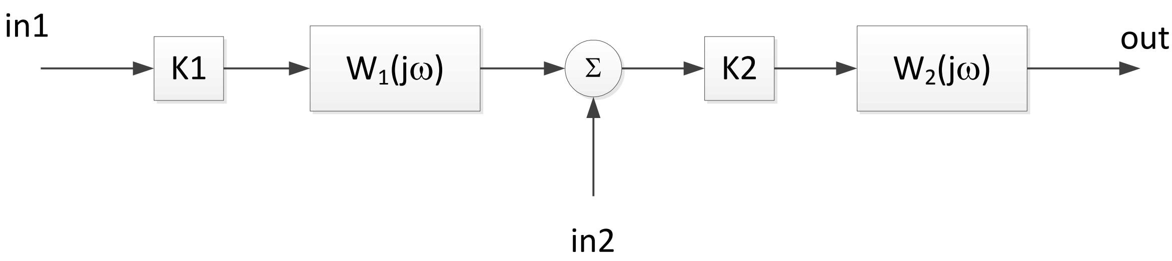


Fig. 3 Two successive regulation paths

For obtaining the frequency responses in first case, two experiments with two different combinations of coefficients K1 and K2 must be performed (Fig. 2). For example $(K1 = 15\ K2 = 5)$ and $(K1 = 10\ K2 = 5)$. From obtained data “FreqChar” software calculate two frequency responses, by solving system of two equations with two unknowns. It is well known from control theory, that scheme on figure 2 could be transformed to scheme on figure 3. So, in this case two experiments with to different combination of coefficients ($K2$ and $K1 \cdot K2$), should be made. Thus frequency responses of $K2 \cdot W2(j\omega)$ transfer function and $K1 \cdot K2 \cdot W1(j\omega) \cdot W2(j\omega)$ transfer function are obtained. Knowing $K2 \cdot W2(j\omega)$

frequency response, frequency response of $K1 \cdot W1(j\omega)$ transfer function could be got by control theory rules implementation.

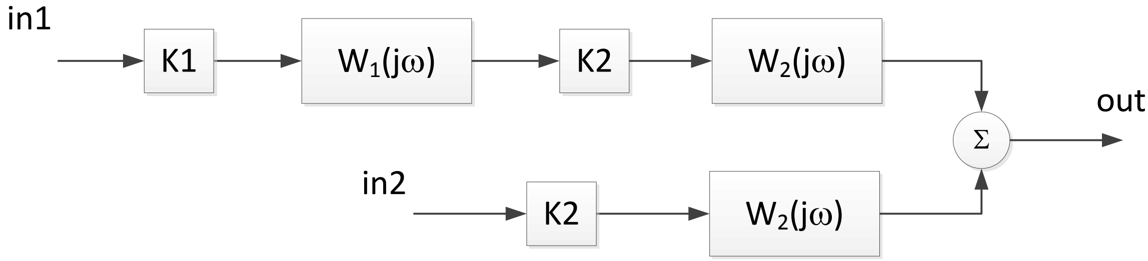


Fig.4 Transformed scheme

IV. Approbation of the method

Method was approbated by obtaining the frequency responses of AVR and PSS mathematical models (Fig. 5), implemented in RTDS. Obtained frequency responses were compared with frequency responses of the same model calculated in MathCad software. On figures 6-8, are shown some results of experiments, calculated frequency responses, and relative error. As it can be seen from figures, relative error doesn't exceed 5%.

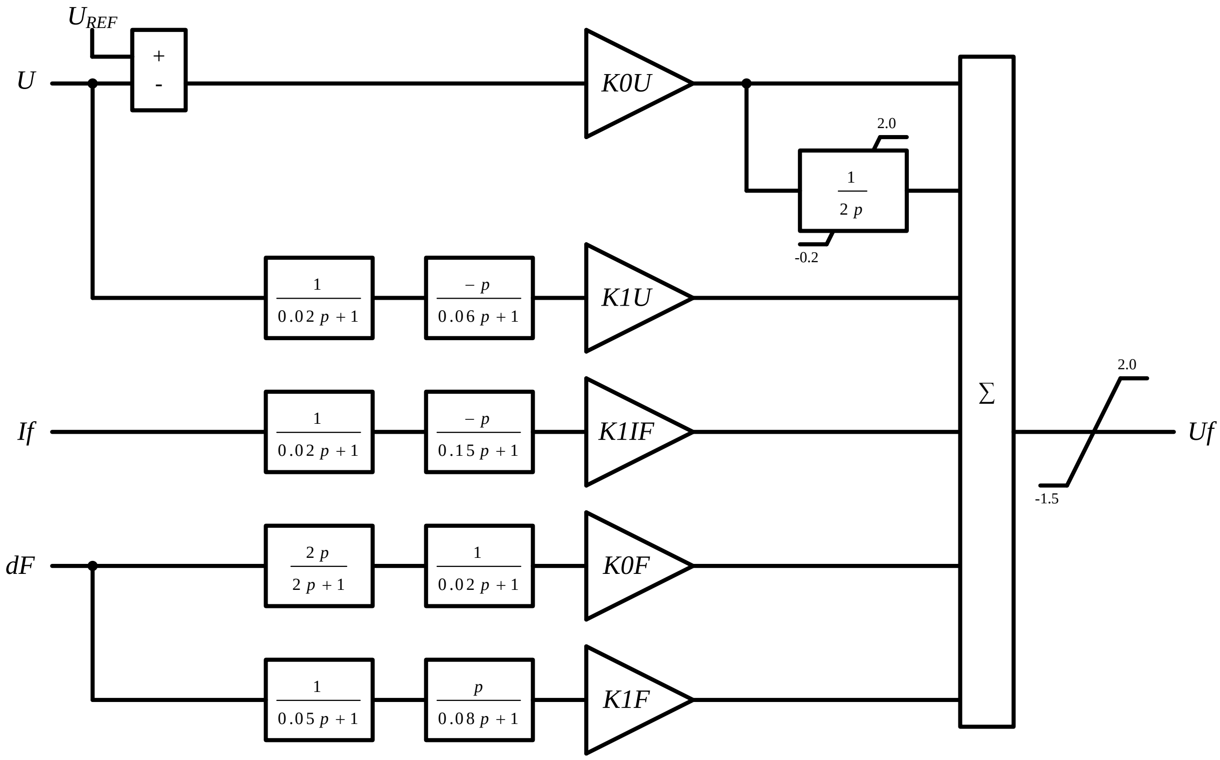
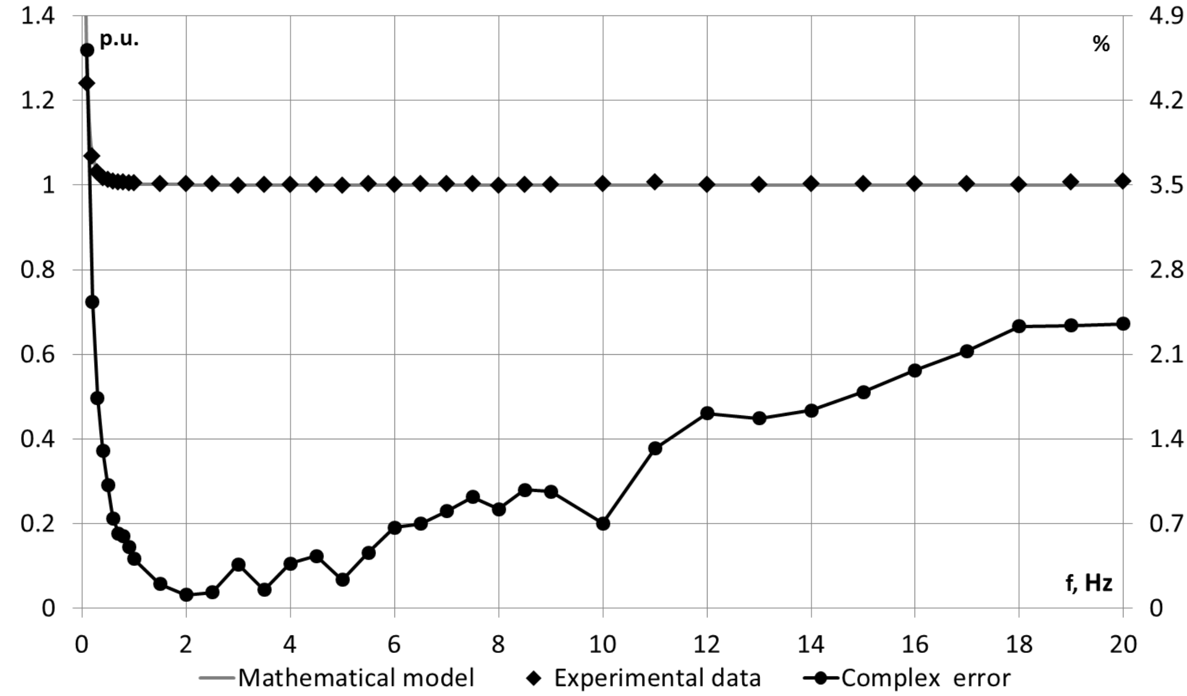


Fig. 5 Mathematical model of AVR which was created for approbation of method of obtaining frequency responses

p-Laplas operator; dF – frequency deviation of generator terminal voltage; K0U – amplification coefficient of PI regulator; K1U – amplification coefficient of generator terminal voltage derivation ; K1IF – amplification coefficient of field current derivation; K0F – amplification coefficient of frequency deviation of *generator terminal voltage; K1F – amplification coefficient of frequency derivation of generator terminal voltage;*



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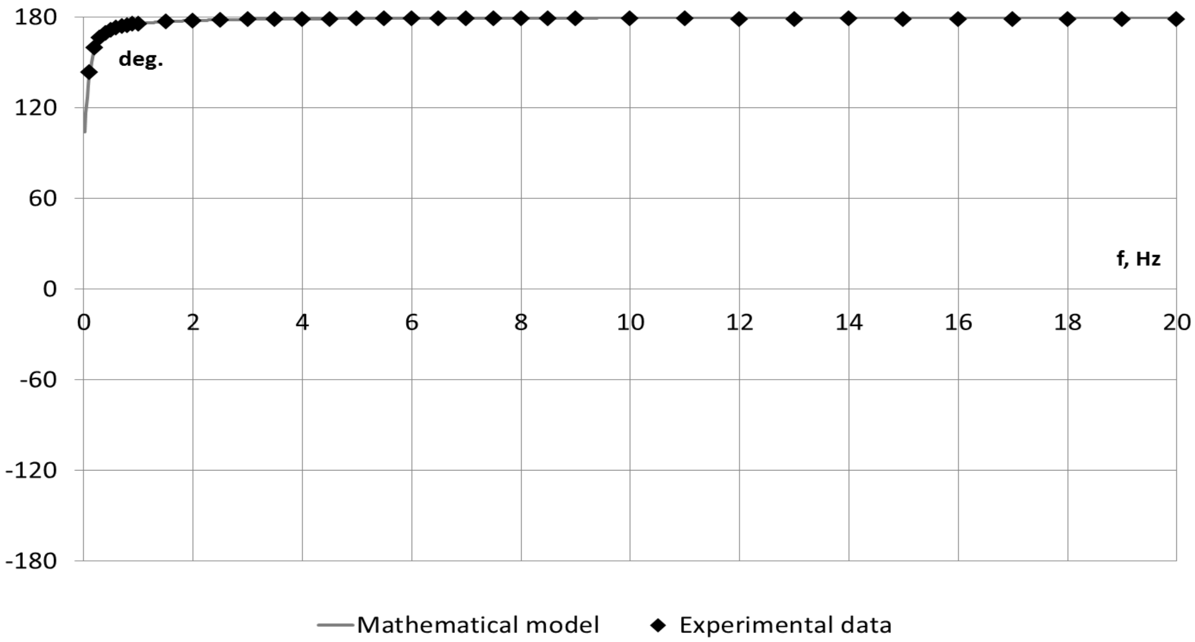

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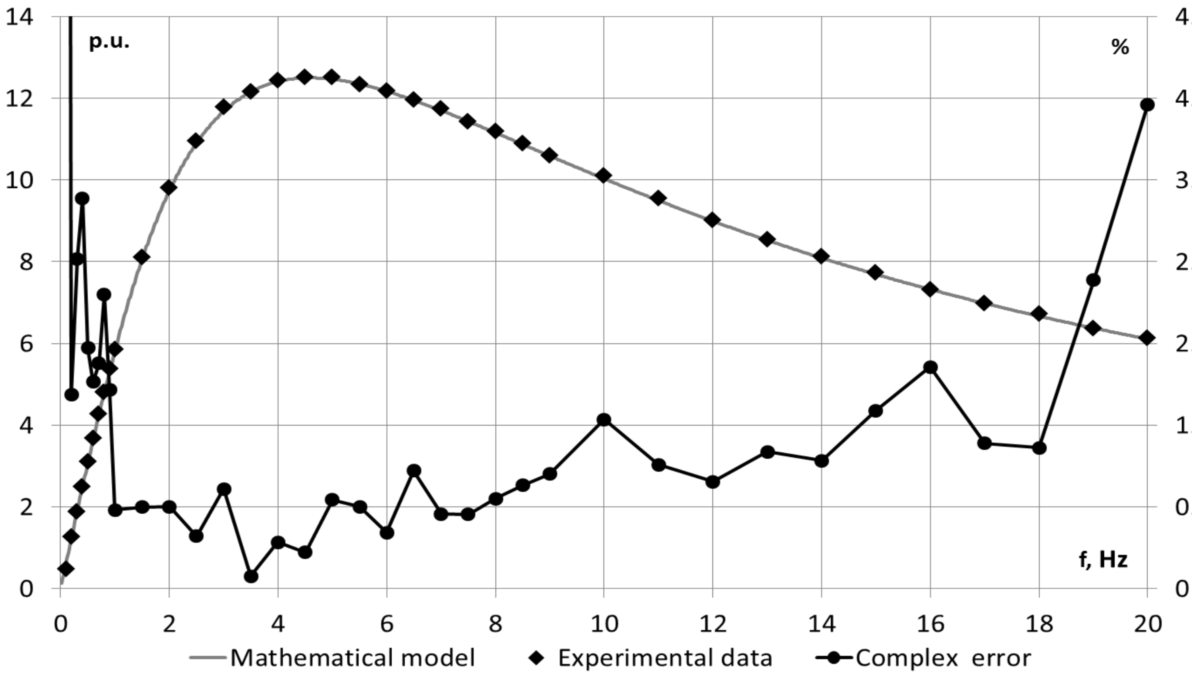
Fig. 6 Amplitude and phase versus frequency plot of PI regulator



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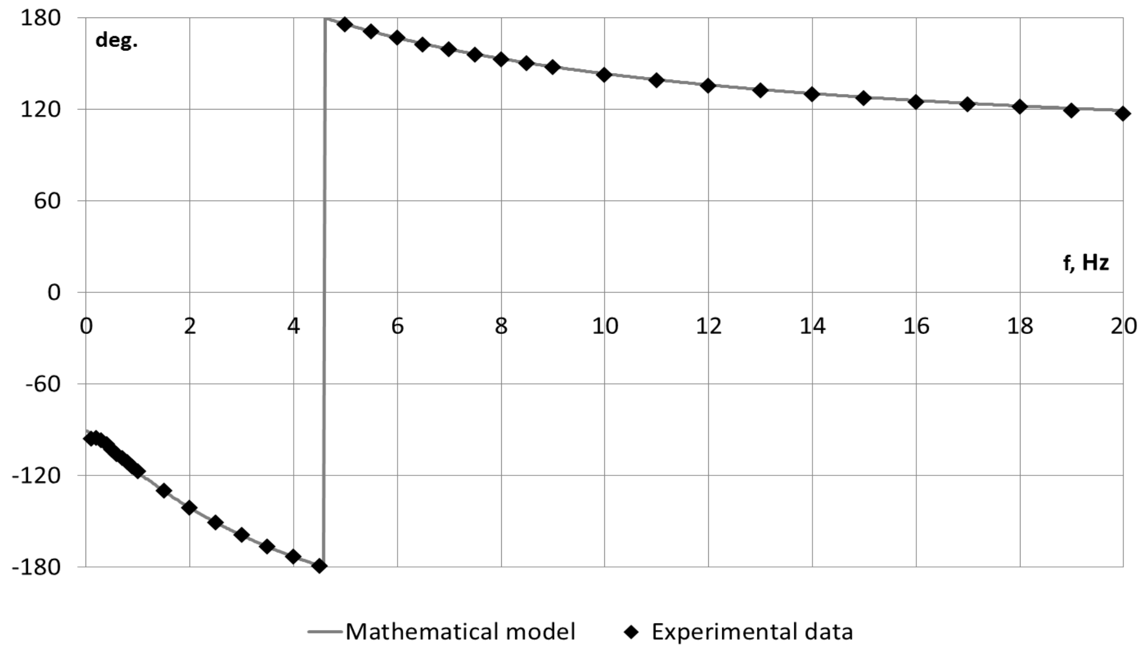

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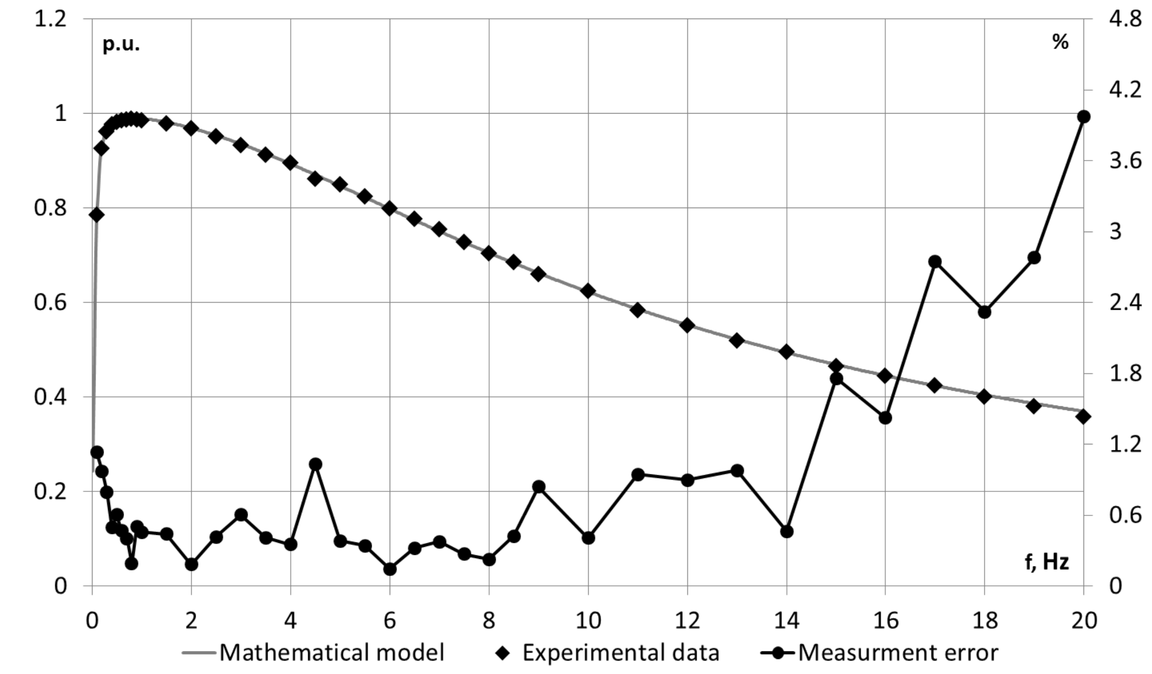
Fig. 7 Amplitude and phase versus frequency plot of terminal voltage derivation regulation path



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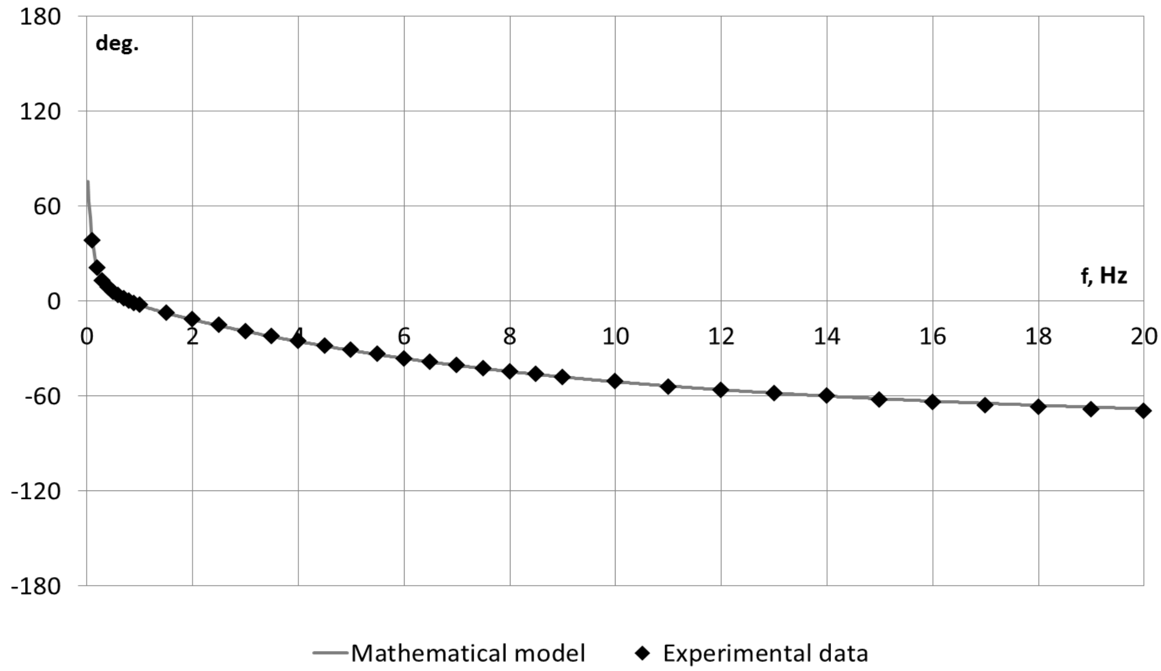

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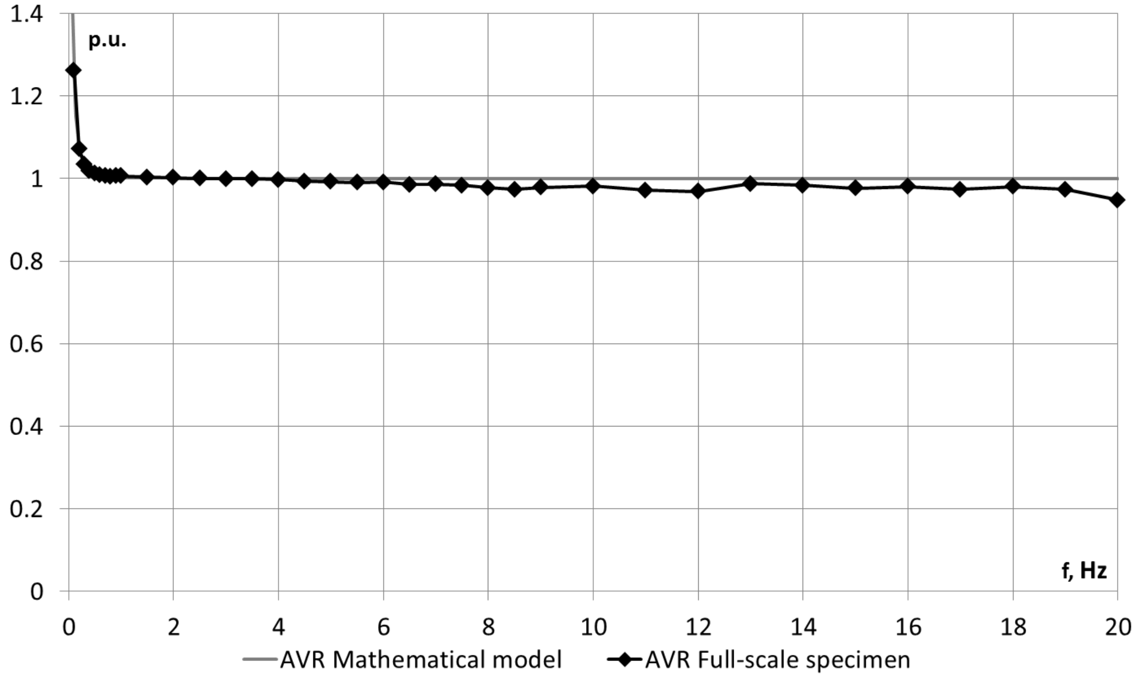
Fig. 8 Amplitude and phase versus frequency plot of terminal voltage frequency deviation regulation path

V. Some results and analysis

Some AVRs and PSSs have been already tested, and their frequency responses were obtained. On figures 9-11 frequency responses of AVR/PSS and its mathematical model are shown. Mathematical model was created based on data provided by manufacturer.



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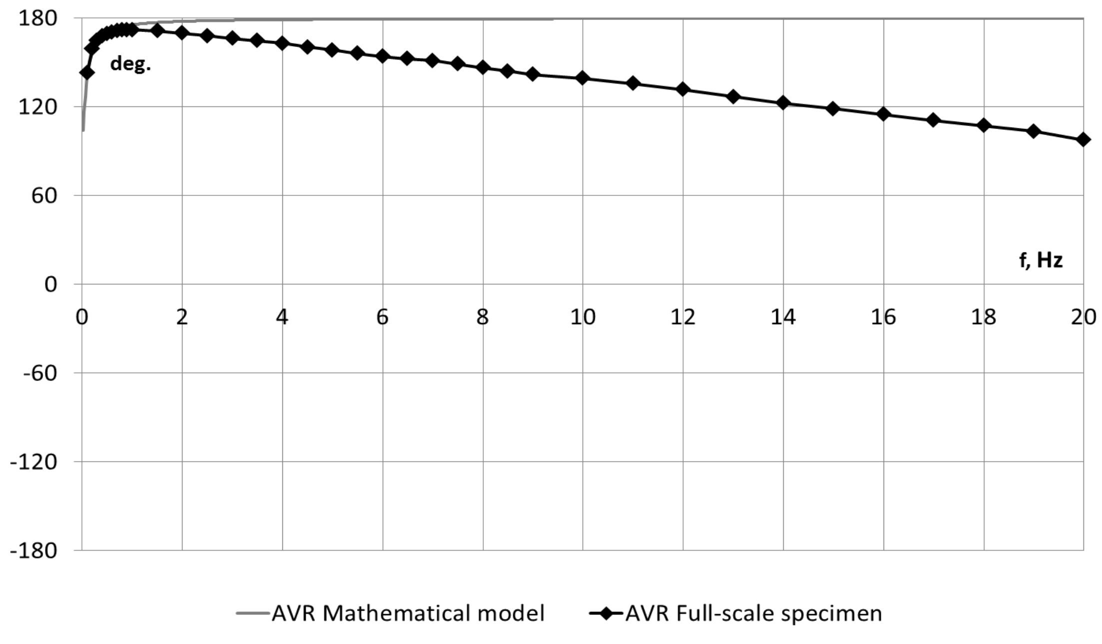

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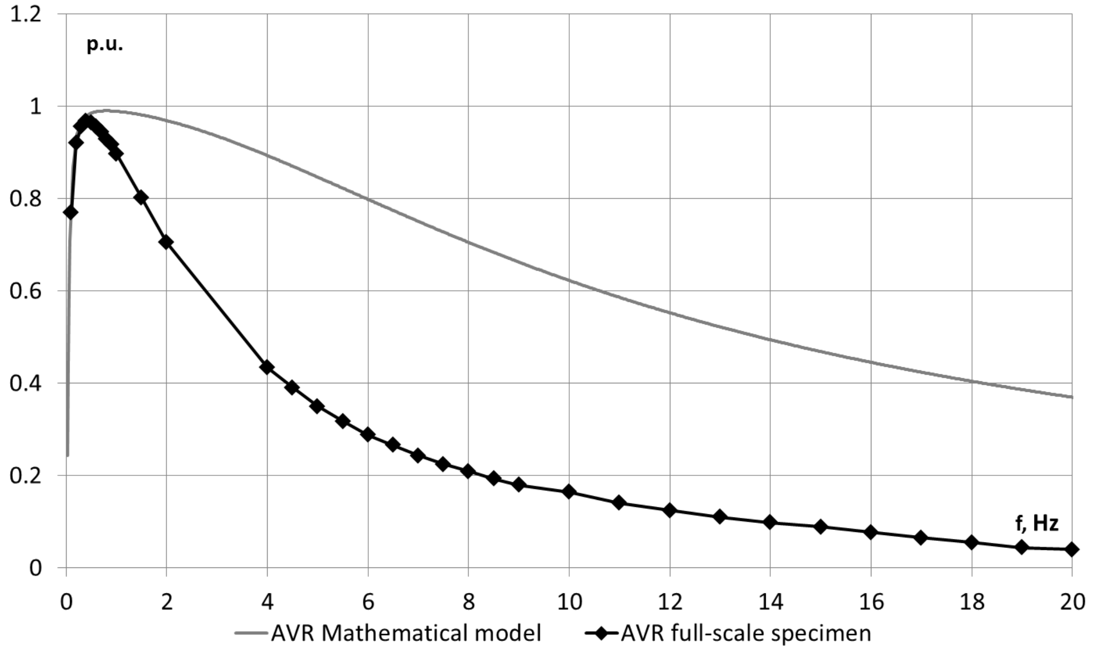
Fig. 9 Amplitude and phase versus frequency plot of PI regulator of AVR full-scaled specimen



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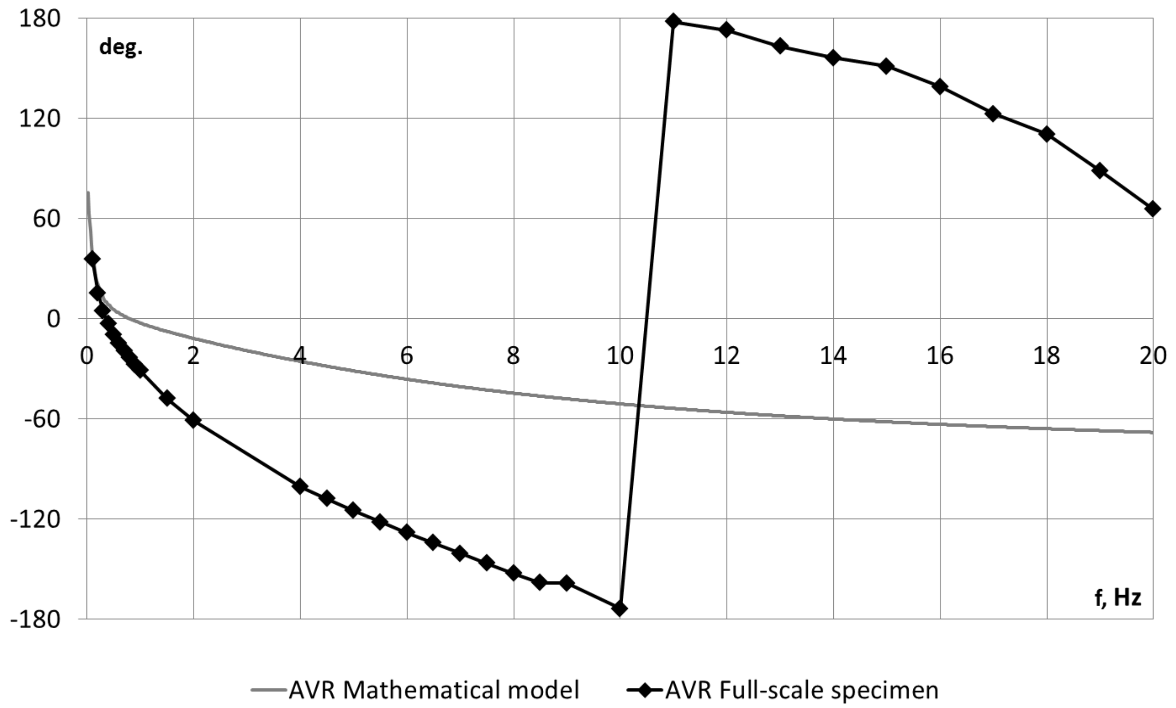

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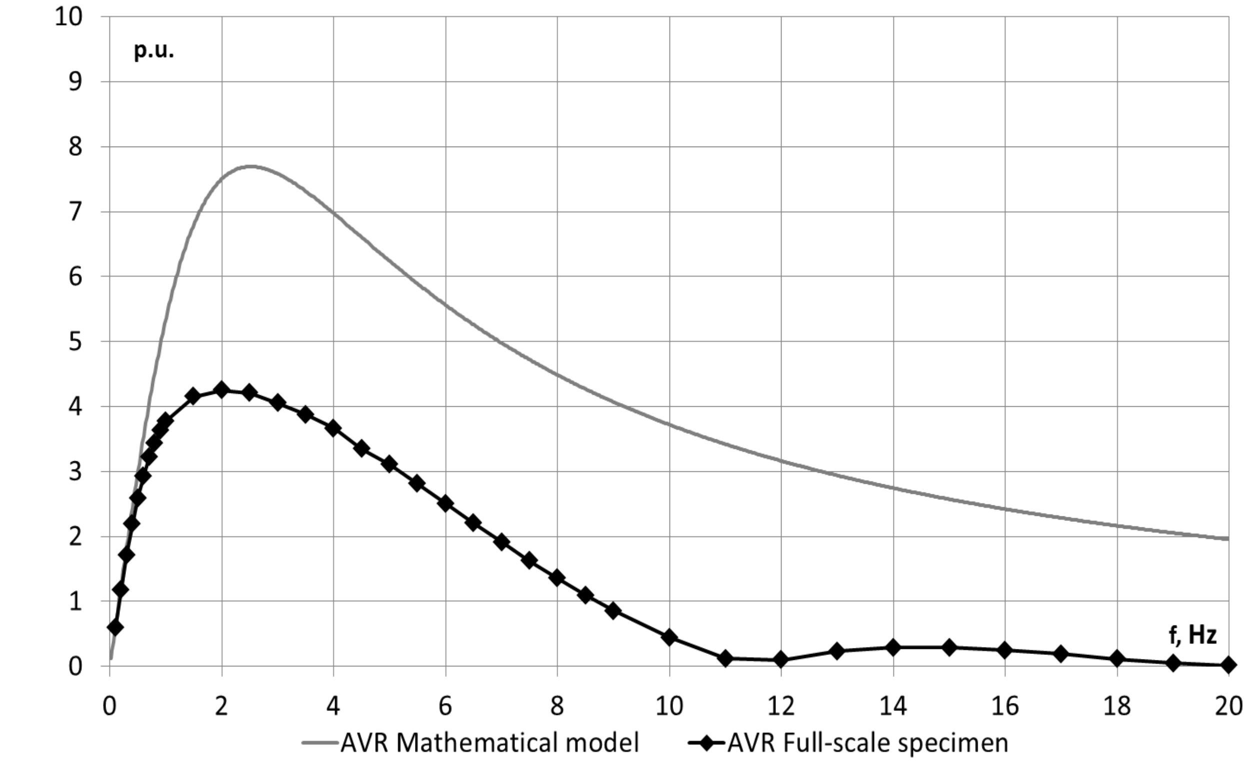
Fig. 10 Amplitude and phase versus frequency plot of terminal voltage frequency deviation regulation path of AVR full-scaled specimen



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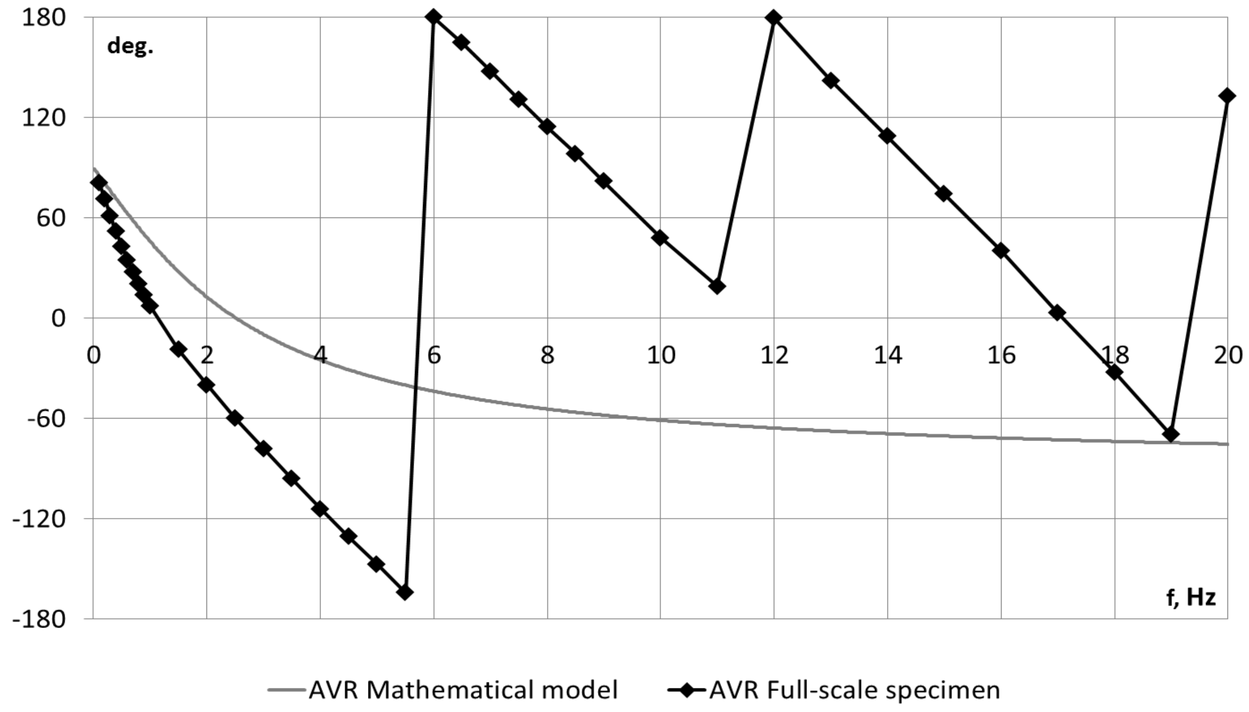

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Fig. 11 Amplitude and phase versus frequency plot of terminal voltage frequency derivation regulation path of AVR full-scaled specimen

As it can be seen from figures, frequency responses of full-scaled specimen of AVR/PSS can differ greatly from frequency responses of corresponding mathematical model even within frequency range 0-3 Hz. These differences may be related to the fact, that manufacturers doesn't consider digital signal processing in there models.

This method can be applied in the future for verification and refinement of existing AVRs and PSS mathematical models, which are used in calculations of electromechanical transients.

VI. Conclusion

1. Described method can be used for obtaining the frequency responses of AVRs and PSSs
2. RTDS Simulator can be used for obtaining the frequency responses of AVRs and PSSs and for verification of its mathematical models
3. Described method and RTDS Simulator can be used for creating more refined mathematical models.

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