After the RISEnergy Transnational Access, Users are required to submit a User Report. This should be done within 4 weeks after the Access is completed unless otherwise agreed. The User Report will be given to the User(s) by the WP2 leader. The report contains sections related to the work performed, the main results and observations that were achieved.

This document should be completed, signed, and sent by e-mail to risenergy@for.kit.edu.

Summary questionnaire for Users who have been granted Transnational Access (TA) under the RISEnergy project Horizon Europe TA scheme. More information on RISEnergy TA can be found in "General Rules" and in "Access Policy" which can be found on the RISEnergy webpage.

Please complete, sign, and send this form, together with the Cost claim by e-mail to risenergy@for.kit.edu *with title: RISEnergy APP181 - reports.*

General information about the project	
Project title (as used in Application)	Interfacing Algorithm for Switch-mode Amplifiers for PHIL Testing of Renewable Energy Sources
Project number (APPXXX) and acronym (max 15 characters)	APP181, AMPERE
RISEnergy RI(s) accessed	TA25 – ICCS-EES-lab
Keywords (up to five, free text)	PHIL, Stability Modelling, PV, Wind,
Arrival date (in town where RI is located)	18th September 2025, Athens, Greece
Departure date (from town where RI is located)	19th October 2025, Athens, Greece
Starting date of Access (first day at RI)	19th September 2025, Athens, Greece
Finishing date of Access (last day at RI)	17th October 2025, Athens, Greece
Number of days not using the RI (during the above period)	10 days
Reason for not using RI those days (describe)	Saturday and Sunday
Number of days using the RI	21
Number of Users granted Access (group size)	2
Comments	
User	
User group leader or sole applicant (user group member 1)	
First name	

Last name	
Affiliation / Employer	
Country of Employer	
E-mail	
User travelling to RI?	
Comments	

User group member 2

First name	
Last name	
Affiliation / Employer	
Country of Employer	
E-mail	
User travelling to RI?	
Comments	

Access Summary Report - work performed and initial results

Brief description of the objectives of your project (up to 200 words)

Switch-mode power amplifiers are increasingly being used in the Power Hardware-in-the-Loop (PHIL) simulations of converters for their better efficiency, higher power density, and smaller size than the linear power amplifiers. In the linear amplifier, the semiconductor switches operate in the linear region (e.g., class A, class B, and class AB), whereas semiconductor devices in the switch-mode power amplifier operate in either fully ON or fully OFF states. These differences in the operating principles lead to contrasting characteristics between the linear and switch-mode power amplifiers. Due to the non-linearity, the existing transfer function-based interfacing algorithms will not be accurate when switch-mode amplifiers are used specially under large disturbances in the system. Even though there are limited literature available on switch-mode amplifier-based PHIL, they mostly assume the amplifier to be linear which is not correct. Currently, very few literatures focus on the switch-mode amplifier-based interfacing algorithms considering non-linearity. This proposal fills the gap. The objective of this proposal is to, at first, characterize the dynamic behaviour of the switching amplifier available in the NTUA lab. After characterizing the amplifier behaviour, this proposal aims to develop an interface algorithm to improve the dynamic performance of the PHIL simulations with switching amplifier.

Activities performed (up to 600 words)

The objective is to first characterize the dynamic behaviour of the switching amplifier. To understand the dynamics of the switch-mode power amplifier (TriPhase) along with the dynamics of the input output (IO) cards of the RTDS, different types of input signals were fed to the amplifier as input from the RTDS. In each case, the input and the amplifier output, which is fed back into the RTDS were measured.

The different input signals which were given as input inside the RTDS were

1. A sinusoidal voltage of 1 pu.
2. A modulated sine wave, with an amplitude modulation 0.1 pu.
   $((0.29 + 0.029\cos(\omega t))\ \cos(\omega t + 0.1\cos(\omega t - \pi))$

3. Frequency ramp down of the sinusoidal input at 1Hz/s till 49 Hz and Frequency ramp up at 1Hz/s till 51 Hz.
4. Voltage step-down from 1 pu to 0.9 pu and 0.75 pu.
5. Voltage amplitude exponential decay 1 pu to 0.75 pu.

In each case, the disturbances were applied on different points of wave on the sinusoid. The zero crossing of the sinusoid is detected and from zero, the disturbance is applied at different instants on the waveform is measured. The degree on the sinusoid is changed from 0 degrees, which is the first zero crossing, to 360 degrees, which is 0.02 seconds from the zero crossing.

The input and output (fed back) voltage data obtained from the RTDS were used to fit a model to represent the dynamics of the power amplifier along with the input output cards. The system identification toolbox of MATLAB was used to fit a model for the amplifier.

For the system identification toolbox, the input and output data needs to be specified. Both linear models and nonlinear models can be fit for the input and output data.

The toolbox can be used to fit both linear models like transfer function and state space to the input and output data and also the nonlinear models like Hammerstein-Wiener and Nonlinear ARX models with non-linearities including polynomial non-linearities, sigmoid functions, wavelet networks, and also machine learning techniques like polynomials, saturation, dead zone, neural networks, gaussian processes (GP) and Support Vector Machines (SVM). The model obtained for the data was used to design a controller, which can compensate for the dynamics of the power amplifier.

Scientific results (up to 800 words)

For the amplifier data, several models including linear models and nonlinear models were obtained from the system identification toolbox.

One of the criterions for judging the closeness of the model fit to the actual output is the based on the normalized root mean square error (NRMSE). The fit criterion is defined as

$$\text{fit} = \left(1 - \frac{\|Y - Y'\|}{\|Y - MEAN(Y)\|}\right) * 100,$$

Where, Y is the measured output and Y' is the estimated model output.

The model that has the best fit percentage, defines the dynamics of the amplifier best. The structure of the HW model and the NARX models, are shown in Fig.

The best model fit for the different models achieved were,

1. For a simple sinusoidal input voltage, the data fit achieved is around 98 %
2. For an amplitude modulated sine wave, the data fit achieved is around 95%
3. For a frequency ramp up and down, the data fit achieved is around 98%
4. For a voltage step down, the data fit achieved is around 92%
5. For the exponential decay, the data fit achieved is around 94%

Fig.1 shows the estimated model output and actual data. Table - 1 compares fit percentage for different models estimated using the voltage stepdown data as it is the case with the lowest fit percentage.

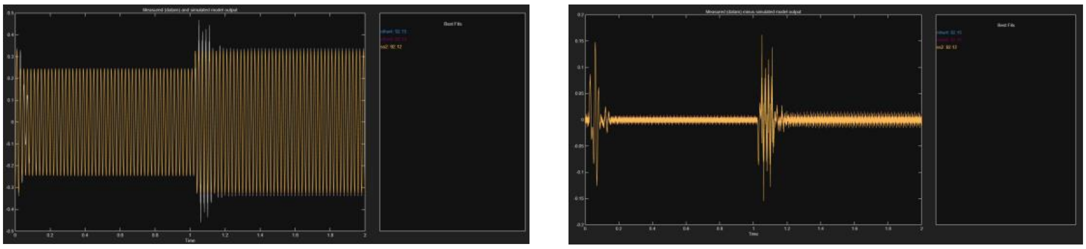

Fig.1: Model Fit percentage and error (measured data – simulated data)

Table 1: Fit percentage for different estimated models

Model Type	Non-Linearity		Regressor Type	Order of the Linear Model	Fit (%)
	Input	Output			
Linear (ss2)	-	-	-	4	92.12
Non-Linear HW (nlhw9)	Polynomial (10th order)	-	-	5	92.15
Non-Linear HW (nlhw4)	Neural Network	Neural Network	-	3	92.15

As the fit percentage of the models obtained by the addition of non-linearity were very close to the linear dynamics, the linear model obtained was used to design a compensator.

Using the model, a compensator was designed to compensate for the dynamics of the amplifier. Fig. 2 shows the digital compensator designed.

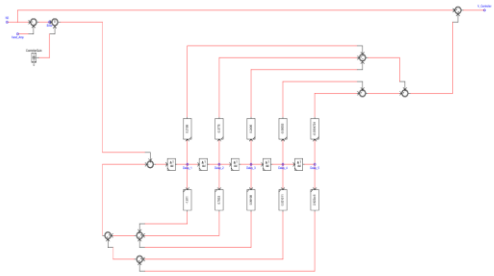

Fig.2: Compensator designed in RSCAD

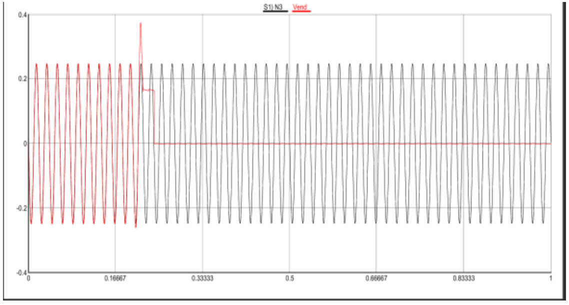

Fig.3: Voltage response after turning on the compensator

Fig.3 shows the input voltage and the voltage response of the amplifier before and after turning on the compensator.

Interpretation of the results (up to 400 words)

As mentioned in the previous section, different kinds of disturbances were applied to the amplifier as an input from the RTDS and the output voltage of the amplifier was captured. From the results it is evident that for the disturbances like the frequency ramp down, the amplifier behaviour is almost linear as the model fit is around 98%, for a linear model. So, if the PHIL application is a frequency ramp down, the amplifier can be modelled using a linear model. For the amplitude modulation and the exponential amplitude decay type signals, the amplifier model fit was around 95% fit. So, if the PHIL application involves testing with the signals of this kind, a linear model fit may work.

For voltage step down and step up, it was observed that the amplifier behaviour is highly non-linear. The amplifier cannot be modelled as a linear model for the studies if the testing involves step changes in voltage. Using the estimated amplifier dynamics, the a compensator was designed and implemented in the RTDS which was not stable. Further investigation is necessary regarding the stability of the PHIL system with the switch mode power amplifier, with a compensator. After TA, we are trying to improve the model of the amplifier for the voltage step down.

Also, if the PHIL testing is to be used for testing hardware for their response during transients, it is important to come up with the metrics for the accuracy of the PHIL simulation that can judge the PHIL testing during transients.

Main achievements during the TA related work (up to 250 words)

This work aimed to identify the dynamics of the switch-mode power amplifier and compensate for the dynamics. During the TA, different signals that can be used as probing signals for obtaining the dynamic model of the power amplifier were identified. The different signals that were used are the common types of disturbances against which the hardware might need testing. The signal structure used for the amplifier testing are similar to the signals mentioned in IEEE std C37.118 1-2011. Also, the different kinds of models that can be fit to the data in MATLAB were identified. The disturbances for which the linear models may be used and the disturbances for which the linear model will no longer give correct results were also identified. Modelling of the amplifier is important while studying the accuracy and the stability of the PHIL simulation. Using simplified linear models for the amplifier, accuracy of the PHIL simulation can be studied, and the stability of the PHIL simulation can be easily understood. Also the nonlinear models can be used for more accurate modelling of the amplifier and the PHIL simulation and in cases where the testing involves voltage step down etc.

Data Management

The experimental data have been stored at NTUA's own facilities and in a OneDrive folder in Sarasij Das's work account.

The experimental data obtained during the testing are the instantaneous voltage input data to the power amplifier and the instantaneous voltage output of the amplifier fed back into the RTDS at a sampling rate of 10 μs.

The data collected/stored includes figures in PNG and PDF formats of all the experimental results, as well as CSV files containing the numerical values of these data during the tests. This data will be used to generate the results and analysis of the joint publication between the host and the user group explained in the previous section.

Difficulties during the TA related work (up to 250 words)

No difficulties were faced while carrying out the experiments and obtaining experimental results. NTUA staff were available and extremely helpful in carrying out the experiments. Also, the equipment at NTUA was available all the time. Because of the complete non-linear behaviour of the switched-mode power amplifier for some disturbances, it was difficult to obtain a dynamic model, that could completely represent the behaviour of the power amplifier and design a compensator to compensate for the dynamics of the Power Amplifier.

Despite the above-mentioned difficulties, as mentioned in the previous sections, we were able to come up with a dynamic model of the Amplifier at least for some types of disturbances, and it has also helped us to identify new lines of research that would improve on the results obtained in this work.

Intended publications

We intend to publish and present the outcomes of this work at the IEEE PES General Meeting. This conference is one of the most influential international forums for researchers, industry experts, and utilities working on power systems innovation. Presenting at this conference will allow us to disseminate the findings to a broad audience engaged in grid modernization, PHIL development, and converter-interfaced generation.

By sharing the improved modelling framework for switch-mode power amplifiers and its implications for real-time simulation accuracy and PHIL stability, we aim to contribute to ongoing efforts toward reliable integration of renewable and inverter-based resources. Engagement at IEEE PES GM will help ensure the work has practical impact, supports industry adoption of more robust PHIL practices, and aligns with the wider push towards smart grid innovation and decarbonization.

Expected impact

In this work, the behaviour of switch-mode power amplifiers under different kinds of disturbances is explored. Power Hardware-in-the-Loop (PHIL) testing is becoming increasingly popular worldwide for evaluating the performance of converter-interfaced renewable generation. Switch-mode power amplifiers are now widely used in PHIL simulations due to their improved controllability, flexibility, and cost effectiveness. However, the behaviour of the amplifier directly affects the stability and accuracy of the PHIL simulation. Understanding this behaviour allows appropriate compensation strategies to be applied.

Accurate modelling of switch-mode power amplifiers is therefore essential. By selecting a suitable amplifier model depending on the application, the accuracy limits of the PHIL setup can be evaluated, and the overall PHIL stability can be correctly assessed. Furthermore, when PHIL simulations involve large disturbances, the use of appropriate amplifier models becomes critical for validating the fidelity of the results.

Real-time simulation and Hardware-in-the-Loop techniques enable testing and validation under conditions very close to real operation, allowing industry to de-risk the implementation of new smart grid technologies. This capability accelerates product development cycles and supports faster deployment of innovative solutions, ultimately contributing to the decarbonisation and modernization of power systems.

Conclusions / additional comments

This work aimed to characterize the dynamic behaviour of the switch-mode power amplifier available and develop an interface algorithm to improve the dynamic performance of the PHIL simulations with the switch-mode power amplifier. During the work, it was identified that the amplifier behaviour is different for different types of input signals. So, depending on the application, the amplifier can or cannot be modelled as a linear model or a non-linear model.
For the applications involving signals with amplitude modulation, frequency ramp down and the exponential amplitude decay type signals, a linear model fit may work.
For voltage step down and step up, the amplifier behaviour is highly non-linear. The amplifier cannot be modelled as a linear model. So, some non-linear models and controls need to be used for such kind of applications. If the PHIL testing is to be used for testing the devices for transients, it is important to come up with the accuracy metrics that can judge the PHIL testing during transients.

Did you complete the European Commission User questionnaire?
☑ *Yes* ☐ *No*

Feedback – HSE, Ethics and Satisfaction

Please rate on a scale from 1 (excellent) to 5 (poor). Feel free to provide additional comments

Practical information on how to apply for Transnational Access and the overall application process	1 (excellent)	2	3 (neutral)	4	5 (poor)
	☑	☐	☐	☐	☐
Comment					
Information provided, once your project was accepted, on how to proceed	1 (excellent)	2	3 (neutral)	4	5 (poor)
	☑	☐	☐	☐	☐
Comment					

Support received at the site(s) regarding technical/scientific matters and logistics	Have you got sufficient support from the RI staff during the project? If not, please, specify the problems. ☑ *Yes* ☐ *No*
Please specify any problems	
RI extension / upgrades required	In your opinion, is the RI needed to be upgraded? If yes, please give an explanation. ☐ *Yes* ☑ *No*
Please specify	
Problems with local regulations	Have you had any problems with regulations of the visited RI owner (HSE, lab working hours, etc.)? If yes, please, specify ☐ *Yes* ☑ *No*
Please specify	
Health and safety issues	Did you encounter any health or safety issue during your research? Please provide details. ☐ *Yes* ☑ *No*
Please provide details	
Environment & Ethics	Did your research involve the use of elements that may cause harm to the environment, to animals or plants? Please provide details. ☐ *Yes* ☑ *No*
Please provide details	

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<tr><td>Environment & Ethics</td><td>Did your research deal with endangered fauna and/or flora and/or protected areas? Please provide details.
☐ Yes ☑ No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Environment & Ethics</td><td>Did your research involve the use of elements that may cause harm to humans, including research staff? Please provide details.
☐ Yes ☑ No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Environment & Ethics – Dual use</td><td>Does your research have the potential for military applications? Please provide details.
☐ Yes ☑No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Environment & Ethics – Misuse</td><td>Does your research have the potential for malevolent /criminal/terrorist abuse? Please provide details.
☐ Yes ☑ No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Environmental issues</td><td>Were any potentially dangerous substances (materials / gases etc.) released into the environment (atmosphere, water, or land)? Please provide details.
☐ Yes ☑ No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Ethics issues</td><td>Are there any other ethics issues that should be taken into consideration? Please specify
☐ Yes ☑ No</td></tr>
<tr><td colspan="2">Please provide details</td></tr>
<tr><td>Overall impression of communication and interaction after finishing your TA and related work</td><td><table>
<tr><td>1
(excellent)</td><td>2</td><td>3
(neutral)</td><td>4</td><td>5
(poor)</td></tr>
<tr><td>☑</td><td>☐</td><td>☐</td><td>☐</td><td>☐</td></tr>
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<tr><td colspan="2">Comment</td></tr>
<tr><td colspan="2">Suggestions for facilities not included in RISEnergy which you would use for your research</td></tr>
<tr><td colspan="2">None</td></tr>
<tr><td colspan="2">Suggestions how RISEnergy can improve future TA programme, how to make the TA more impactful and how to enable the achievement of high TRL levels</td></tr>
</table>

None

<table>
<tr><td colspan="2">Feedback – Pro-active Innovation Support</td></tr>
<tr><td>Awareness</td><td>Did you know about the pro-active innovation support of RISEnergy?
☒ Yes ☐ No</td></tr>
<tr><td colspan="2"><i>[Please specify how you learned about the pro-active innovation support]</i></td></tr>
<tr><td>Personal experience</td><td>Have you taken advantage of or benefited from the pro-active innovation support?
☒ Yes ☐ No</td></tr>
<tr><td colspan="2">[<i>Please provide details]</i></td></tr>
<tr><td>Information/service provided by the pro-active innovation support?</td><td><table><tr><td>1 (excellent)</td><td>2</td><td>3 (neutral)</td><td>4</td><td>5 (poor)</td></tr><tr><td>☒</td><td>☐</td><td>☐</td><td>☐</td><td>☐</td></tr></table></td></tr>
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I declare that the above provided information and especially that information on the number of days visited the RI is correct.

☒ *I have read the RISEnergy privacy policy for participation in the RISEnergy TA and consent to participation and the associated data processing.*