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Technical Report TA User Project

HARSH

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Abbreviations

AFE	Active Front End
DER	Distributed Energy Resource
FFT	Fast Fourier Analysis
PHIL	Power Hardware In the Loop
SCR	Short Circuit Ratio
TA	Trans-national Access
VSC	Voltage Source Converter

Executive Summary

This report was commissioned to examine the harmonic stability of voltage source converters (VSCs) during sympathetic transformer inrush condition. The real-field inrush experiment of 250kVA transformer was carried out to capture the transient behavior of transformer in the time domain. Then the harmonic state-space modeling technique was further employed to modeling non-linear effect inrushed transformer in the frequency domain, which permits the relatively rapid evaluation of harmonic stability for a large number of system operating conditions. The effectiveness of the proposed modeling methodology and harmonic stability assessment is then verified by hybrid virtual and physical hardware test, which combined hardware in the loop (HIL) and real power converter groups.

The research draws attention to harmonic instability in the form of resonances or abnormal harmonics that aroused by the dynamic interaction between the VSCs and its isolation transformer. Further investigations reveal that the energization of one transformer may lead to the saturation of the other transformers within short electrical distance. In this case, the equivalent impedance of the transformer seen by the VSC is highly nonlinear, and the dynamic interactions between the VSC and nonlinear transformer impedance tend to bring in the sustained or even amplified harmonics. Moreover, designing the VSC control system to be immune from the adverse consequences of harmonic instability during the sympathetic transformer inrush requires examination of a large number of cases, which can be difficult when using only time-simulation tools.

The impedance-based method provides a powerful yet intuitive way to address the harmonic instability problem between the power electronics converters and passive components in the grid, which has been already heavily used in power electronics communities. This research project extends the impedance-based method to include the non-linear effect of transformer inrush core saturation. The harmonic-state space impedance models are developed both for the inrushed transformer and the VSC, and thereby the theoretical harmonic stability assessment can be performed in the frequency domain. Meanwhile, the detailed nonlinear models of transformers and VSC are established in the Opal-RT, and then high-bandwidth power converters are controlled by Opal-RT to mimic the dynamic interactions between the transformers and VSC in the real world.

According to the theoretical analysis and realistic experimental test using the field-measured data, the report concludes that the harmonic instability can occur during the sympathetic transformer inrush condition, and harmonic-state-space impedance models allow rapid evaluation of harmonic stability hazards for a large combinations of control parameters, circuit parameters, and different operating conditions, which paves the way for the future system-level harmonic stability analysis.

1 General Information of the User Project

User Project acronym	HARSH
User Project title	Harmonic stability under sympathetic transformer inrush
Name of the ACCESS PROVIDER	DNVGL Netherlands B.V.
INSTALLATION name	Flex Power Grid Lab
Name of the ACCESS PROVIDER representative	Erik de Jong
Name of the User Group Leader	Dongsheng Yang
User Group	1) Xiongfei Yang 2) Dongsheng Yang
Home Institution of the User Group Leader:	Aalborg University, Department of Energy Technology, Denmark
Access period	03.04.2018 – 13.04.2018
Nº of Access Days	5

2 Research Motivation

The research project addresses the harmonic stability challenges with the ever-increasing power electronics connected to the modern power grid, where new analytical methods (i.e. power electronics input impedance based method) and its validations are essential to safeguard such transition and establish trust between power electronics communities and the power system communities. Built upon the latest research outcomes from the power electronics societies, the research project extends the impedance-based method to include the non-linear effect of transformer inrush core saturation paving the way for the future system-level harmonic stability analysis.

2.1 Objectives

1. Validate the impedance-based method in a realistic power grid setup with physical transformer and power grid connected.
2. Advance the small signal stability method to include typical power system non-linear effect (i.e. transformer inrush core saturation effect)
3. Identify gaps between theoretical analysis and validation measurement obtained from the physical lab test.

2.2 Scope

The research project will study the harmonic stability of VSCs during transformer inrush or sympathetic transformer inrush condition. Figure 1 depicts the research project test setup. Two transformers are connected to the 10kV level, CB1 is in close position to connect the equipment under test (EUT), back energized by the DC source, with the public AC grid. The EUT is realized by a 200kW power hardware in the loop (PHIL) Egston amplifier controlled by OPAL-RT (real-time digital simulator).
When CB2 suddenly closes, Tr2 will introduce disturbances caused by the inrush current. During the energization period of Tr2, the proposed test setup is illustrated by Figure 2, where Tr2 can be represented by a non-linear load with time-varying impedance. In fact, seen from the EUT towards the network, during the transformer inrush, the grid impedance will contain a time-varying non-linear component until the transformer inrush period completes. Since the existing research reported so far tends to simplify the grid impedance as a passive linear component, the proposed setup allows the investigation of grid impedance considering the non-linear effect during transformer inrush, a critical yet realistic scenario for offshore wind farm grid.

In fact, when a transformer is energized near another transformer, a so-called sympathetic inrush/resonance condition can be created. The sympathetic inrush condition can be explained by the Figure 3 below, where the inrush current of Tr2 could cause significant voltage distortion when the short circuit power strength at PCC 10kV is low. Due to the voltage distortion at 10kV PCC point, it could cause the Tr1 magnetic flux to go beyond its knee point dragging the Tr1 also into saturation (solid line represents the current distortion for Tr1 whilst the dashed line shows the sinus reference during normal operation). In this complex scenario, looking from EUT into the power grid, grid impedance will become highly non-linear and the overall harmonic stable region is also likely to be quite different from when the grid impedance is linear under normal operating condition. Looking at the offshore wind farm grid nowadays, the highly anticipated power electronics dominant grid is already a reality featuring low short circuit power with a high amount of power electronic devices close to each other. In this regards, the proposed research is highly relevant addressing the industrial challenges today and future, where stability of power electronics dominant is of central importance for the large-scale deployment of renewable generation and efficient power conversations technologies driving the transition towards sustainable and energy efficient future.

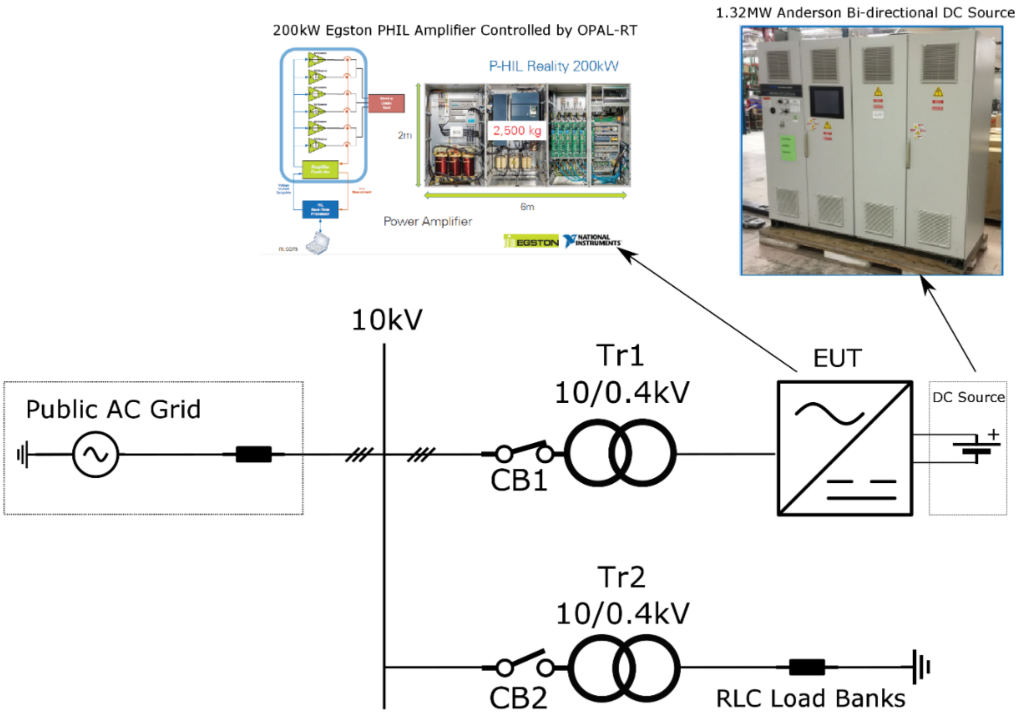


Figure 1 Research Project Test Setup

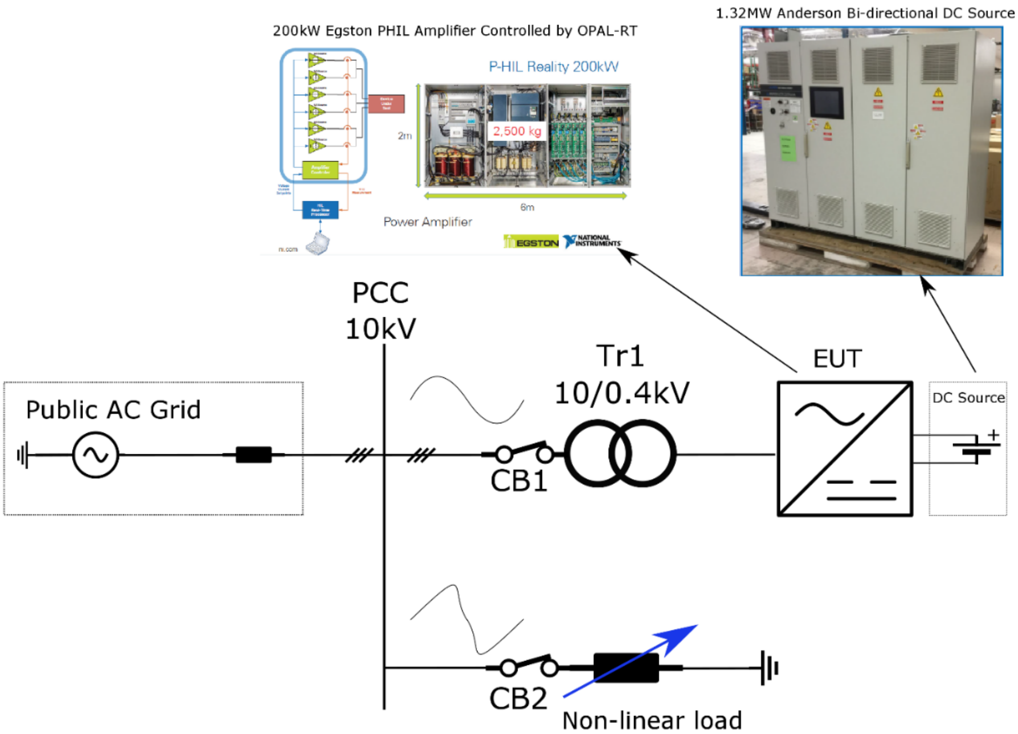


Figure 2 Research Project Test Setup Equivalent Circuit During Transformer Inrush

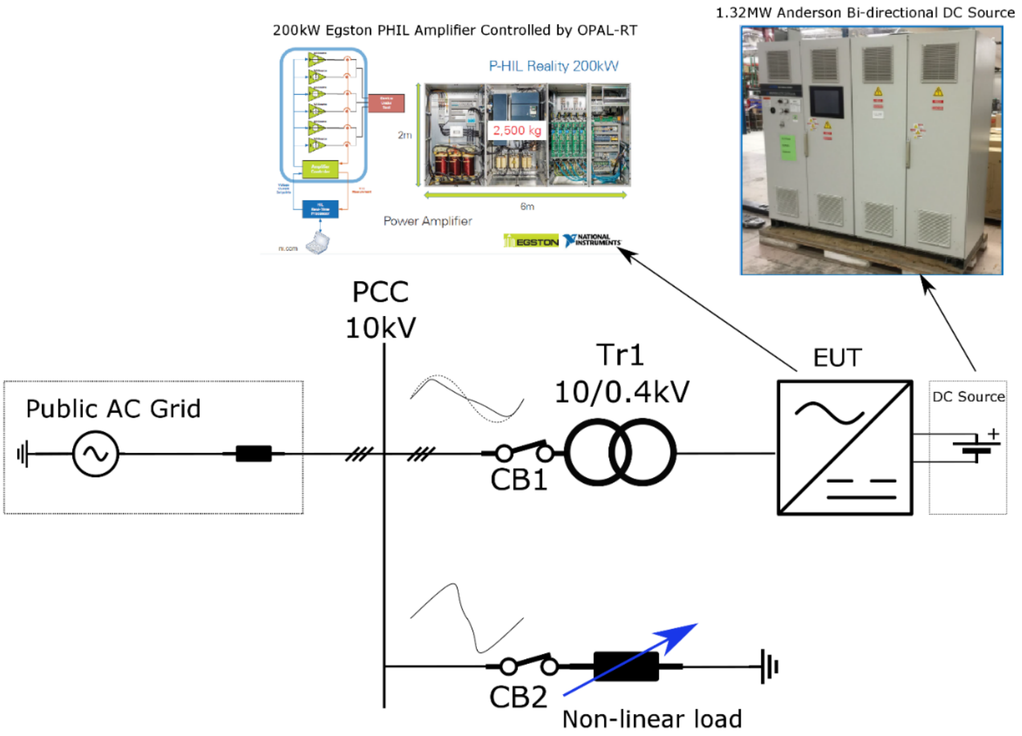


Figure 3 Research Project Test Setup Sympathetic Inrush Condition

3 State-of-the-Art

Voltage Source Converters (VSCs) are increasingly used in electric power grids for efficient energy consumption and renewable energy generation [1]. Compared to electrical machines, VSCs have the wider-bandwidth control dynamics, ranging from the outer power control loops (sub-synchronous frequencies) to the inner current control loop (hundreds of hertz to kHz). The dynamic interactions among the power grid and VSCs tend to cause oscillations in a wide frequency range [2]. To address the stability challenges with the grid-connected VSCs, the impedance modeling and control methods have been developed for dynamic characterization and active stabilization of VSCs [3]-[10]. However, many of the research efforts were dedicated to the stability of the inner current control with LCL- filters [3]-[6], where the influences of current controller and time delay of the digital control system have been thoroughly discussed. Only a few works have recently been reported to include the effects of the grid synchronization and the outer power (dc-link voltage) control loops [7]-[10], [16], [17]. Those control loops are usually designed with a lower bandwidth than the current control, which, together with the grid impedance, tend to result in the unexpected harmonics or resonances near the fundamental frequency [2].

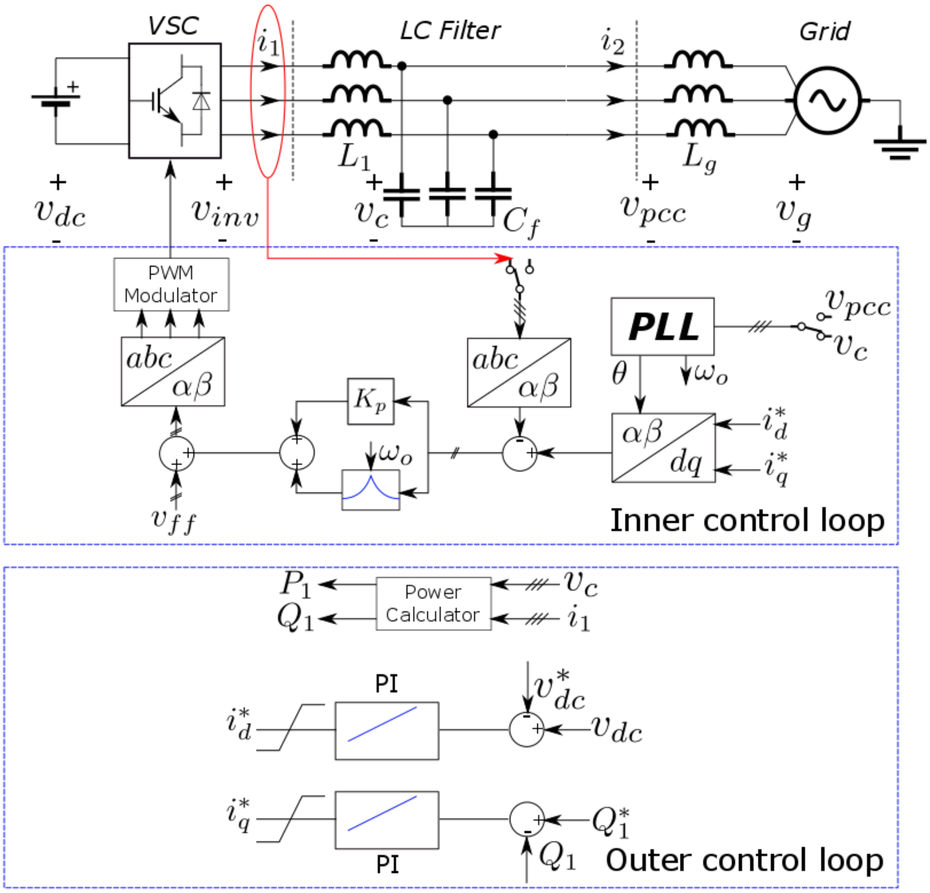
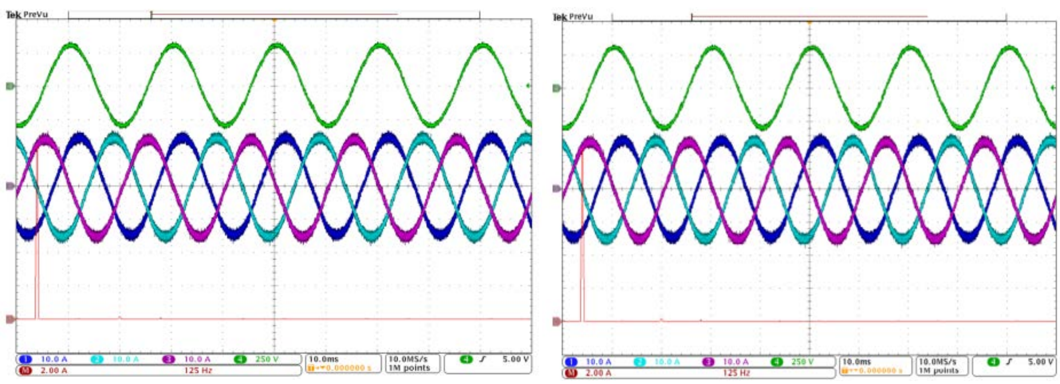
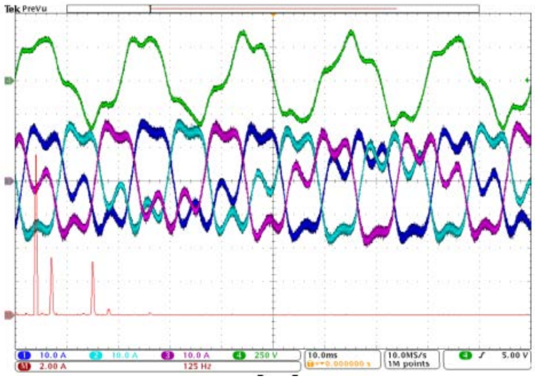


Figure 5 Single Line Diagram of VSC using Proportional Resonance (PR) Control

Figure 5 illustrates a simplified one-line diagram of a three-phase grid-connected VSC, where a constant dc-link voltage (V_{dc}) is assumed, and a parallel LC-type grid impedance is considered. Based on the thorough frequency domain analysis, [18] accurately predicts the instability region of VSC caused by the increase PLL control bandwidth. The analytical results are further confirmed by the time domain experimental results as shown in Figure 6 ((a) and (b) are stable while (c) becomes unstable).



(a) (b)



(c)

Figure 6 Measured PCC voltage and VSC current for the αβ -frame current control. (a) f_{PLL} = 20 Hz. (b) f_{PLL} = 175 Hz. (c) f_{PLL}=330Hz

4 Executed Tests and Experiments

In the project, three experimental tests are carried out in sequence. The first test is to energize the 250kVA SMIT transformer using 10kV public grid under no load condition. Both the voltage and current waveforms at the primary side (10kV high voltage side) are measured and recorded during the inrush procedure. After that, the second test is carried out to examine the sympathetic inrush phenomena between the two transformers by the HIL test using the realistic data obtained from the nameplate and the measurement results. Finally, the third test is conducted to examine the harmonic instability of the VSC during the sympathetic inrush conditions.

4.1 Test Plan

In order to obtain a realistic model for the power transformer, the transient voltage and current waveforms of a 250kVA transformer during inrush condition should be recorded for reference. To implement the inrush test, the following procedures should be carried out step by step:

Step 1: Install the transformer.

Responsible people: Erik de Jong, Dongsheng Yang

First, the transformer should be moved to the appropriate location in the flexible power lab. For security, the transformer should be reliably grounded. Then the transformer will be connected to the 10kV public power grid through circuit break. Since the circuit breaker is paralleled with inrush limiter, the additional circuit breaker should be also series connected with the original circuit break to mimic the real-field energization of the transformer.

Step2: Configure the measurement system.

Responsible people: Rick Scharrenberg, Erik de Jong, Dongsheng Yang

Check voltage and current transducers settings and remove the short-circuit switch for the current transducers. Then the output of the transducers should be connected to the Yokogawa data-acquisition system through the BNC cable. Finally, the GUI of Yokogawa data-acquisition system in the host computer should be configured to record the six channels waveforms with appropriate scaling factors.

Step3: Energize the transformer and record the waveforms.

Responsible people: Erik de Jong, Rick Scharrenberg, Dongsheng Yang

For security, the circuit break with inrush limiter will be used for inrush test to check the correctness of cable connections and the measurement system. After that, the circuit beak without inrush limiter will be used for the inrush test, and the waveforms will be recorded.

As the sympathetic inrush test and harmonic instability test, the tasks can be divided into hardware operation and HIL model implementation. These two parts can be executed independently.

As for the hardware operation, the following procedures should be carried out step by step:

Step 1: Configuration of control interface on the RT-Lab

Responsible people: Alejandra Fabian, Yin Sun, Dongsheng Yang

The major task for the step is to configurate the interface of power amplifier on the RT-Lab to realize the following functionalities: (1) Control a group of power amplifiers (GAMP) as the three-phase voltage sources, (2) Control a GAMP as the three-phase current sources, (3) Parallel operation of the two GAMPs, one as the voltage sources and the other as the current sources, (4) Set the analog output port of Opal-RT to output the measured currents and voltages of GAMP and check them using the Oscilloscope.

Step 2: Operation of the power amplifiers

Responsible people: Dongsheng Yang, Rick Scharrenberg

First turn on circuit break to energization of the transformer for the power amplifiers, and then turn on the cooling system of the power amplifiers and set the temperature reference. After that, check the setting point and run the power amplifiers through the COMPISO user interface.

As for the HIL model implementation, the following procedures should be carried out step by step:

Step 1: Modeling and parametrization of the transformer in the RT-Lab and debugging

Responsible people: Dongsheng Yang, Rick Scharrenberg

To get the realistic model of the transformer with saturation characteristics, both the saturation curves and other parameters, such as leakage inductances, magnetizing inductances, winding resistors should be derived from the known parameters available from the manufactures and measured data from the test. Meanwhile, the saturable transformer model in the RT-Lab library may encounter the well-known numerical instability problem and should be resolved additional effort.

Step 2: Modeling and design of the VSC on the RT-Lab and debugging

Responsible people: Dongsheng Yang, Yin Sun

To accurately model the dynamic behavior of the VSC with fixed system sampling period, the real-time PWM model should be used to calculate the switching instant within the sampling period. Moreover, since the VSC usually adopts the digital control with a different sampling period as the system sampling period, therefore, the re-sampling scheme should be implemented in the RT-Lab.

Step 3: Do the sympathetic inrush test and harmonic instability test

Responsible people: Dongsheng Yang, Rick Scharrenberg

When both saturable transformer model and VSC model are established in the RT-Lab, sympathetic inrush test and harmonic instability test can be performed. First, control one GAMP to mimic the grid with grid impedance and a local load with a transformer, and control another GAMP to mimic the VSC connected with saturable transformer. By turn on/off the virtual circuit break in the RT-Lab, the sympathetic inrush and harmonic instability can be examined in a flexible way.

4.2 Test Set-ups

The Photo of the transformer that used for inrush test is shown Fig. 7. The detailed parameters are shown in Table I.

Figure 7 Photo of the transformer used for inrush test.

Table I Parameters of power transformer under test

	Parameter	Values
S_n	Nominal apparent power	250 kVA
f_0	Nominal frequency	50 Hz
V_{pn}	Nominal voltage at the primary side	10250 V
V_{sn}	Nominal voltage at the secondary side	400 V
I_{pn}	Nominal current at the primary side	14.3 A
I_{sn}	Nominal current at the secondary side	361 A
V_{leak}	The voltage drop on the leakage inductance	4.05%
V_{iso}	Isolation voltage	28 kV
T_n	Working temperature	75 °C
W	Total weight	1270 kg

The configuration of the whole tested system is shown in Fig. 8. As seen, the medium voltage bus Vbus is connected to the 10kV public power grid through the circuit break –Q1 in +MVS1 which can be remotely controlled by the computer. Here, –Q2 in +MVS1 is grounding switch to ensure the Vbus is grounded to guarantee the safety of people when entering the lab.

The circuit breaker –Q1 in +MVS2 and –Q1 in +TR2 are coordinated in this way: –Q1 in +TR2 will be automatically turned on 2 seconds after that –Q1 in +MVS2 is turned on by the remote control on the computer. Thus, in the first 2 seconds after –Q1 in +MVS2 is turned on, the resistor –R1 in +TR2 is series connected in the circuit to limit the potential inrush current, and after that, the resistor –R1 in +TR2 is bypassed by –Q1 in +TR2.

Although the inrush limiter is helpful to protect the transformer, it is rarely used in the real-field application. That's because one the transformer is energized, it will put into service for a long time can last for many years. Therefore, to test the inrush transient without inrush limiter, the circuit breaker –Q1 in +XIREA is also connected in the circuit. If –Q1 in +XIREA is turned on after that the bypass switch –Q1 in +TR2 is already turned on, the transformer will be energized without inrush limiter.

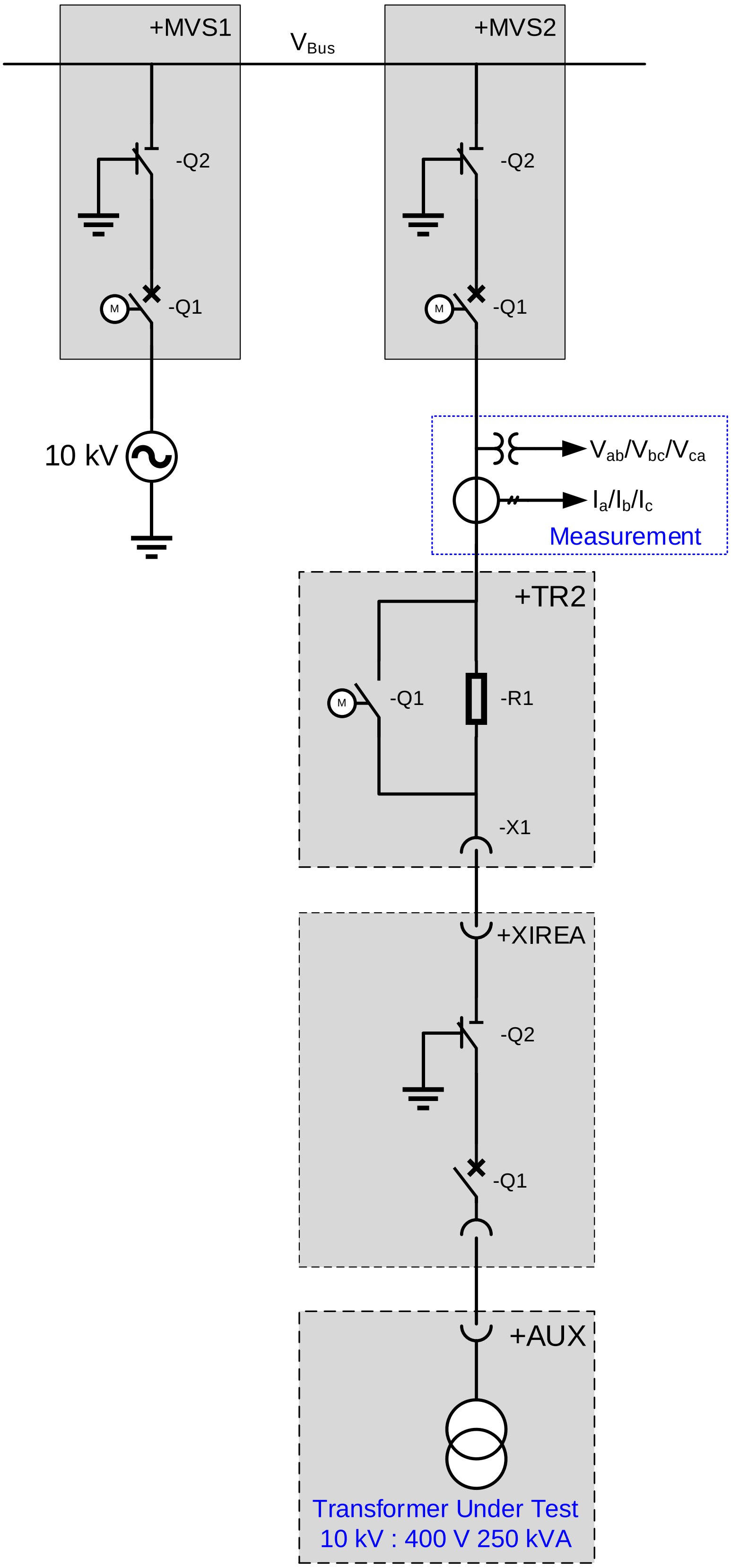


Figure 8 System configuration for the transformer inrush test.

Since the short circuit ratio of 10kV voltage bus is 186 MVA, the peak inrush current can reach a very high value, typically 25~30 times of nominal current value, and it may trigger the overcurrent protection. Therefore, the protection parameters should be set carefully. In this test, protection will be triggered under any one of the following conditions: (1) the peak value of differential mode current reaches 150 A and lasts longer than 50 ms; (2) the peak value of differential mode current reaches 1500 A and lasts longer than 40 ms; (3) the peak value of the common mode current lasts longer than 50 ms.

To measure the three phase voltages and currents during the inrush transient, the voltage and current transducers are installed between the +MVS2 and +TR2, as shown in Fig. 9. The signal transfer ratios of the voltage transducers are 10kV/100V, and the signal transfer ratios of the current transducers are 20A/1V.

(a)

(b)

Figure 9 Photos of measurement devices (a) voltage transducers (b) current transducers

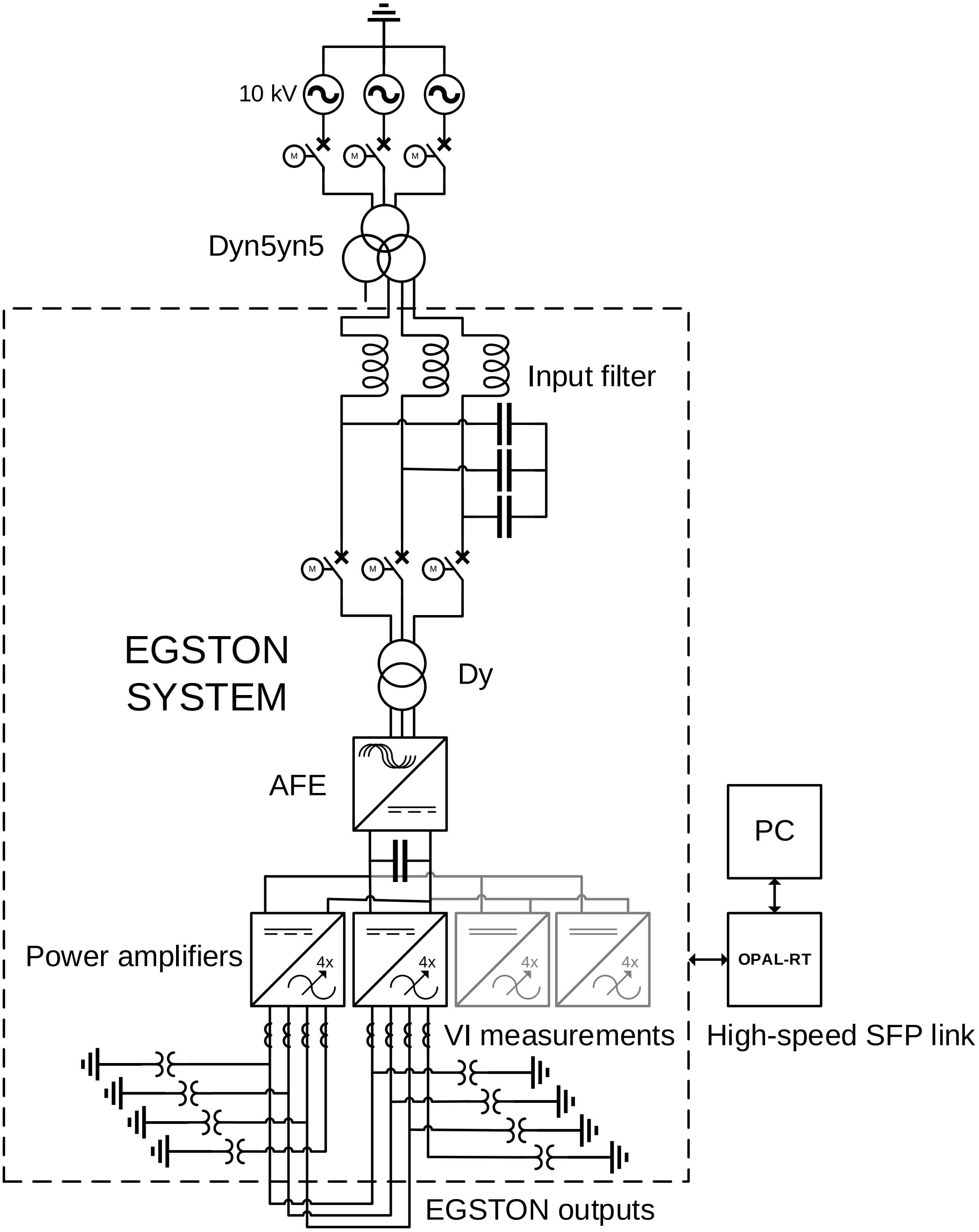


Figure 9 System configuration for the sympathetic inrush test and harmonic instability test

The system configuration for the sympathetic inrush test and harmonic instability test is shown in Fig. 9. Basically, it can be divided into two parts, including the power hardware system and HIL system. The power hardware setup in DNV GL Flexible Power Grid Lab (FPGL) is made up of 200 kVA Egston digital power amplifier, and the HIL system contains OPAL-RT OP5707 real-time digital simulator (includes Xilinx Virtex-7 FPGA VC707).

The digital power amplifier from Egston consists of 4 groups of 4 single phase units (i.e. 16 units) with a total rated power of 200 kVA and a closed-loop bandwidth of 5 kHz. The individual digital power amplifier is realized by 6 interleaved parallel half-bridge converter with an equivalent switching frequency of 125 kHz. The photos of input LC filter, active front, and four groups of power amplifiers in the Egston system are shown in Fig. 10.

(a) (b)

(c)

Figure 10 Photos of Egston system (a) Input filter and power switches (b) Active front end (AFE) (c) four groups of power amplifiers

The OPAL-RT OP5707 real-time digital simulator is capable of electrical power grid real-time simulation and the control algorithm implementation in either RT-Lab v11.2.2.108 or Hypersim R6.1.3.o698. For the close loop PHIL setup, the high-speed SFP communication link is established between OPAL-RT and Egston. Every 4 us, current and voltage measurements are read back from the digital amplifier output terminal to OPAL-RT whilst the voltage and current control signal set-point are sent to Egston digital I/O box. A host PC is connected via asynchronous ethernet to the OPAL-RT target PC. For RT-Lab v11.2.2.108, it is used in combination with Matlab/Simulink 2015aSP1 (32 bit). The photos of OPAL-RT and host PC are shown in Fig. 11

To test the sympathetic inrush and harmonic instability, a back-to-back PHIL setup can be realized by short circuit the terminal of two digital power amplifier output, where one is controlled as a three-phase voltage source to mimic the grid with a local load isolated by a saturable transformer whilst the other is controlled as a three-phase current source to mimic the dynamic behavior of the VSC with a saturable converter transformer.

(a)

(b)

Figure 11 Photos of hardware in the loop system (a) Yokogawa data acquisition system(left) and Opal-RT digital simulator(right) (b) Host PC

4.3 Standards, Procedures, and Methodology

To test transformer inrush with inrush limiters, -Q1 in +MVS2 should be turned on all through the test. To start the test, first turn on the -Q1 of +MVS2 first through the remote control from the computer, thus for the first 2 seconds, the transformer is energized with -R1 limiting inrush current in +TR2. After that -R1 is bypassed by -Q2 in +TR2.

To test the transformer inrush without inrush limiters, -Q1 in +MVS2 should be turned off in the initial state. To start the test, turn on the -Q1 of +MVS2 first through the remote control from the computer. Since -Q1 in +MVS2 is turned off, the transformer is not energized. After 2 seconds, the -R1 is bypassed by -Q2 in +TR2, then turn on the -Q1 in +MVS2 manually, and the transformer is energized with inrush limiter -R1 in +TR2 bypassed.

To test the sympathetic inrush and harmonic instability, the whole system is first tested only using the hardware in the loop until the desirable phenomena is obtained. After that, the whole system is divided into two parts, including the grid with a local load isolated by a saturable transformer, and the VSC with a saturable converter transformer. Then two groups power amplifiers (GAMPs) are used to mimic the dynamic behaviors of the two parts, as well as their interactions in the real world.

The procedures for operating of the power amplifiers are as follows

Case 1: Operation of one GAMP

1. Click the app “CCI”—open the SCADA for Egston (Two terminals will generate automatically which are used to receive the data for sampling system, **do not close them!**)
2. Start CSU—turn on the contactor between grid and transformer to energize the transformer
   (1) Check the “Fan”: green light
   (2) Check the “water level”: green light
   (3) Check the “ESA status”: green light
3.Select the setpoint source:
   (1) Internal-setpoint data is provided by internal AWFG
   (2) External Hil (SFP)-setpoint is provided by the Opal-RT
   (3) Voltage range: ±360V peak value per phase;
   (4) Current range: ±175A peak value per phase;
4.Create new terminal to check the setpoint data
   (1)Check setpoint of GAMP1 by inputting the following command line:
   ~/Desktop/python/CCD $ python CCD_GAMP1.py
   (2) ls-list all the folders, cd-enter into the folder
   (3) Click “control” item in the menu of Dialogue, choose “AWFG” for internal, or “SFP-APP” for external

(4) Check the setpoint value in “Measure” item, which is presented in per-unit with 1000V for voltage base and 250A for the current base

5. Choose the output mode for Group1: three-phase voltage/three-phase current
6. Click “Set config” to turn on the contactor between CDAs and busbar
7. Click “Output PWM” to enable the output of the CDAs in group1.

Case 2: Parallel operation of two GAMPs

1.Power on procedures:

(1) Enable GAMP which served as a voltage source

(a) Set the magnitude to 325V (Peak value of phase voltage)

(b) Enable “Output PWM”

(2) Enable GAMP which served as a current source

(a) Set the magnitude to 0A

(b) Enable PLL, check the frequency

(c) Enable “Output PWM”

2.Power off procedures:

(1) Disable GAMP that served as a current source

(a) Reduce the magnitude to 0A

(b) Disable “Output PWM”

(2) Disable GAMP that served as a voltage source

(a) Disable “Output PWM”

4.4 Data Management and Processing

The data is recorded through the Yokogawa data acquisition system. For the inrush current test, the waveforms of three-phase currents and three-phase voltage sare saved as .csv format file. The scaling factor are set to compensate the transfer ratio of the voltage and current transducers so that the recorded values are equal to the actual value in the system. For sympathetic inrush and harmonic instability test, besides the three phase-current and three-phase voltages of the VSC, the inrush currents of the two transformers are also recorded. All the data are saved as .csv format, and then are import to Matlab and converted to .mat files for further analysis.

5 Results and Conclusions

The voltage and current waveforms of the 250kV transformer during the inrush transient are presented in Fig 12. Since the 300Ω resistor is used at the inrush limiter, the inrush current during energization of the transformer is greatly eliminated with the peak value 10 A.

When the 300Ω resistor is bypassed during the inrush transient, the peak value of the inrush currents is greatly increased, as shown in Fig. 13-Fig.15, where the transient waveforms with three different inrush tests are presented. As seen, the peak value of the inrush current are slightly different for three tests, namely, 63 A, 134A, and 156A, that's because the circuit breaker is switched on at different points of grid voltage waveforms.

The sympathetic interactions between two transformers are shown in Fig. 16. As seen, the energization of the transformer tr2 in Fig.1 will also cause the saturation of the transformer tr 1 nearby. According to the Fast Fourier Analysis (FFT) analysis in Fig. 17, the dominant harmonics for both the transformer currents are 2nd order harmonic. Due to the inherent damping of the transformers, the 2nd order harmonic decays gradually.

When the voltage source converter is connected to the grid through one transformer, the output current is stable without sympathetic inrush of the transformer. When transformer tr2 nearby is energized and introduces the sympathetic inrush for the converter transformer tr1. Due to the dynamic interaction between the saturated transformer and the VSC control system, the output currents and the terminal voltages of the VSC are greatly distorted, as shown in Fig. 18. This confirms that the harmonic instability may happen during the sympathetic inrush condition.

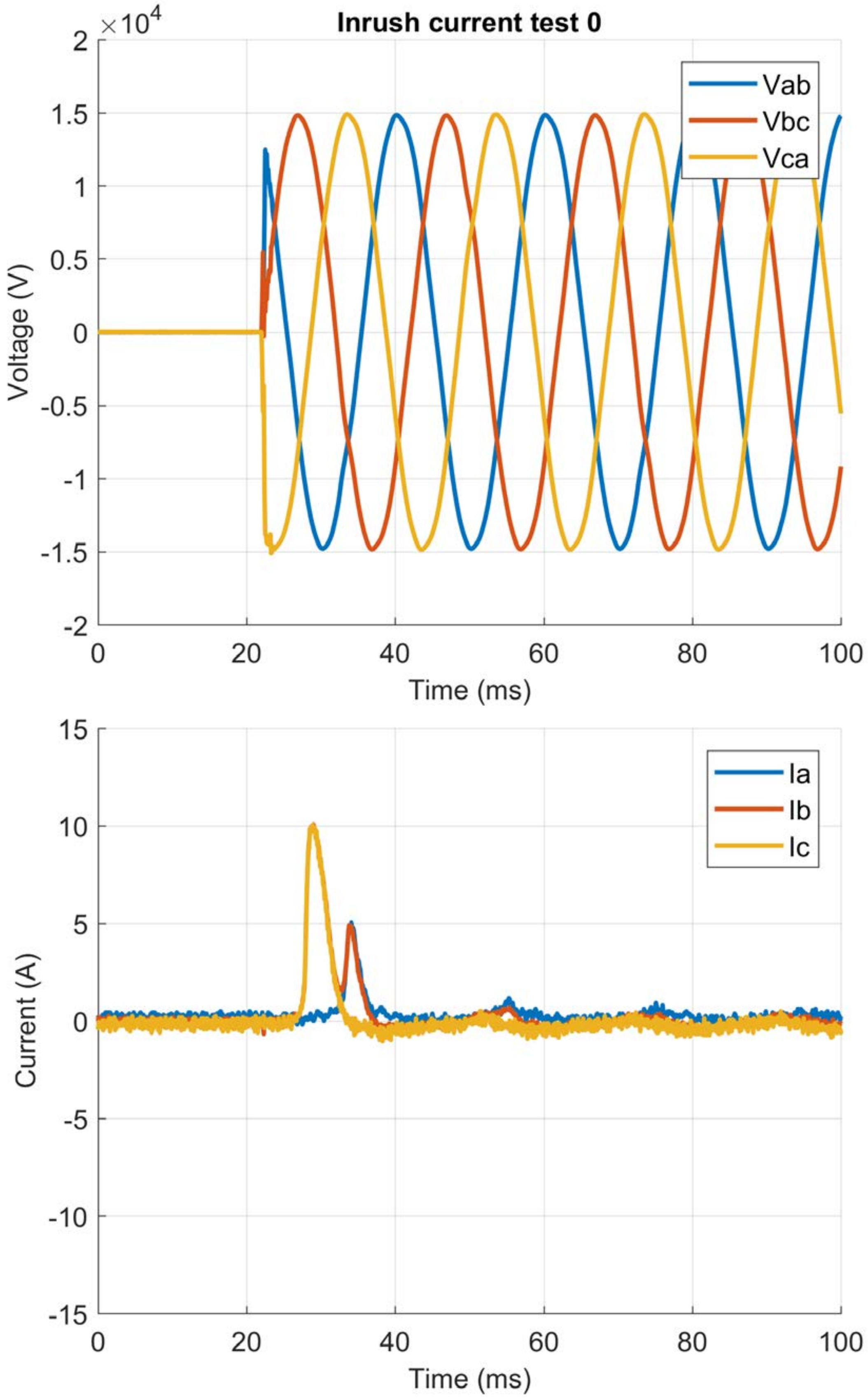


Figure 12 Transformer inrush test with inrush limiter

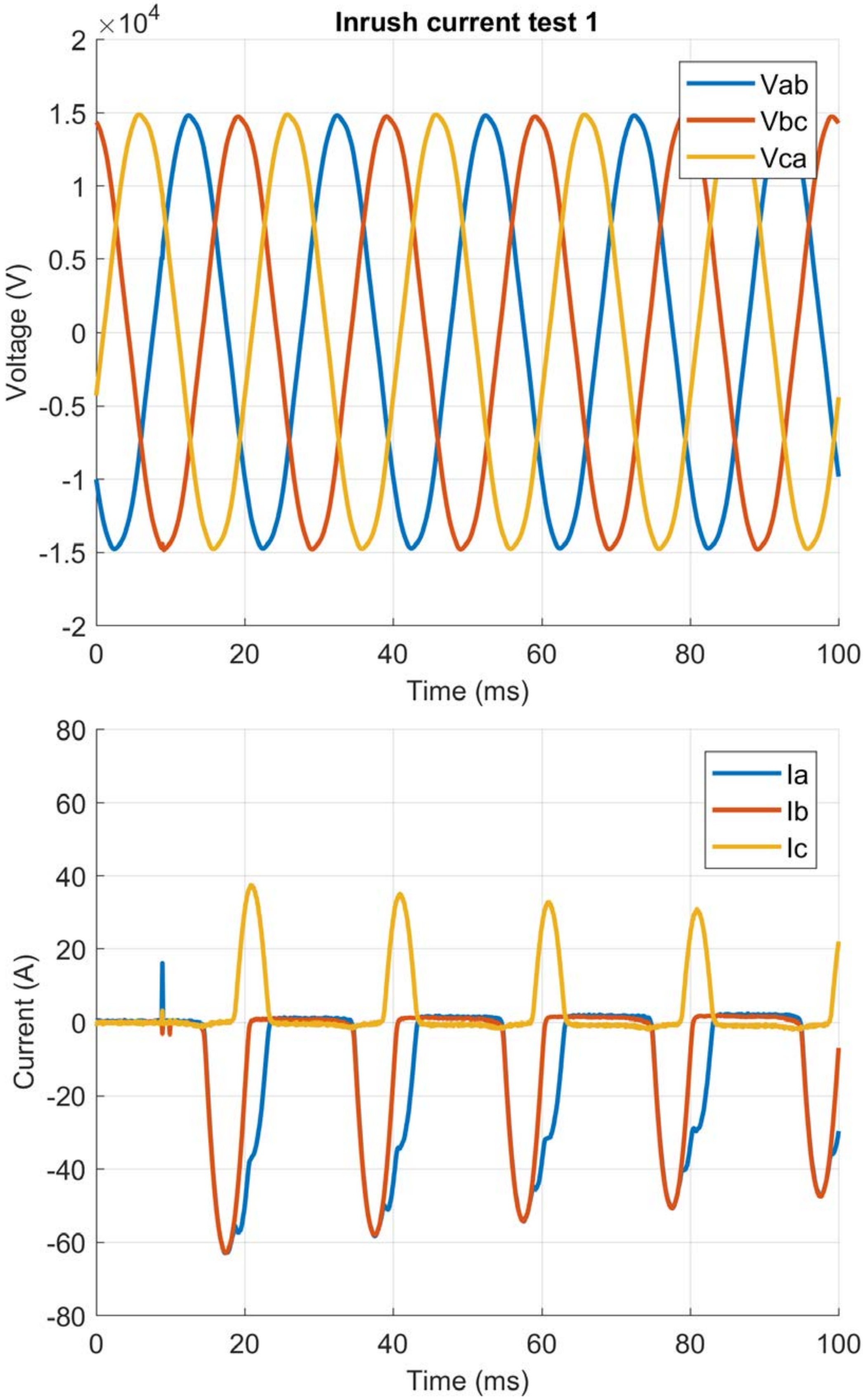


Figure 13 Transformer inrush test without inrush limiter (test1)

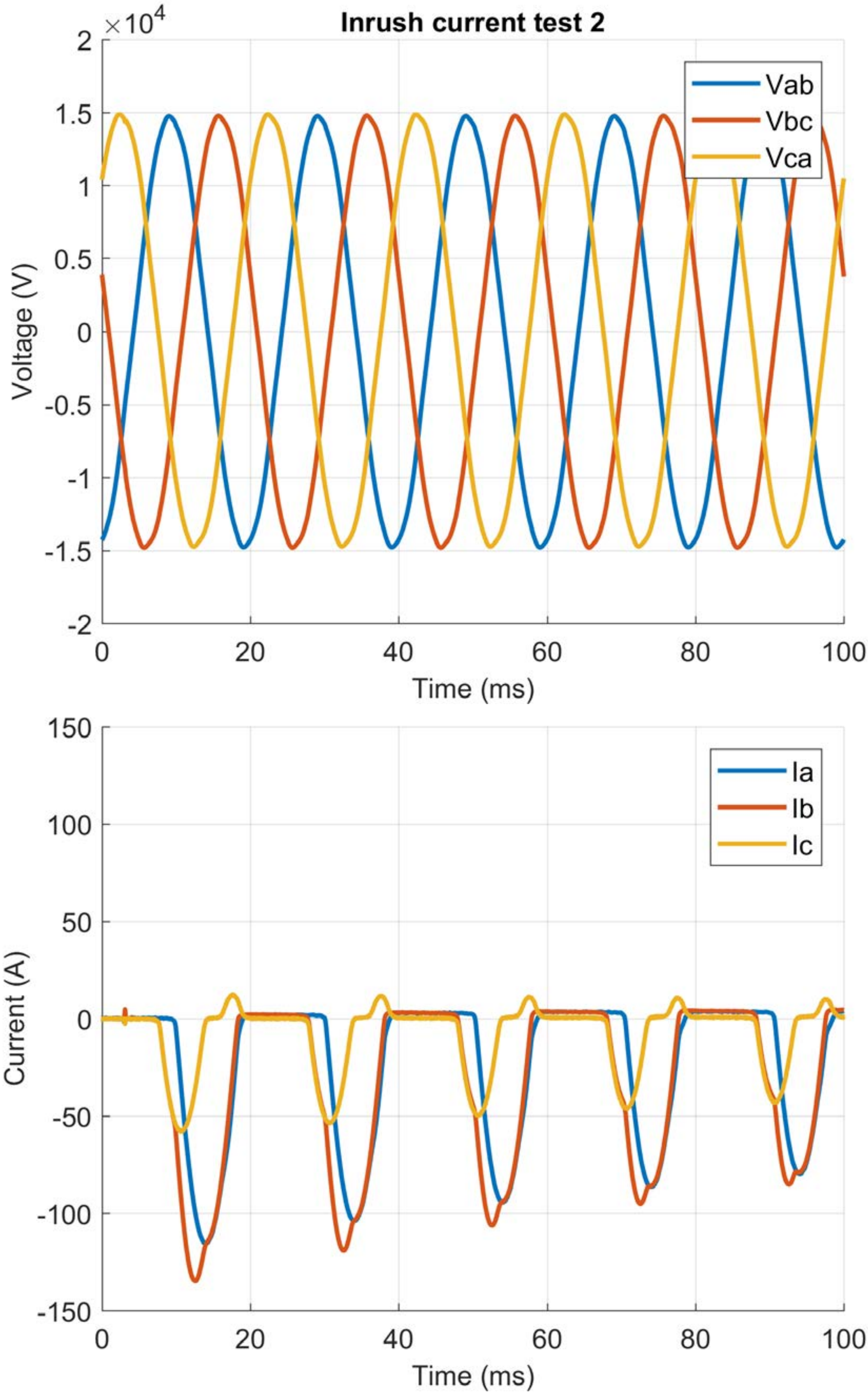


Figure 14 Transformer inrush test without inrush limiter (test2)

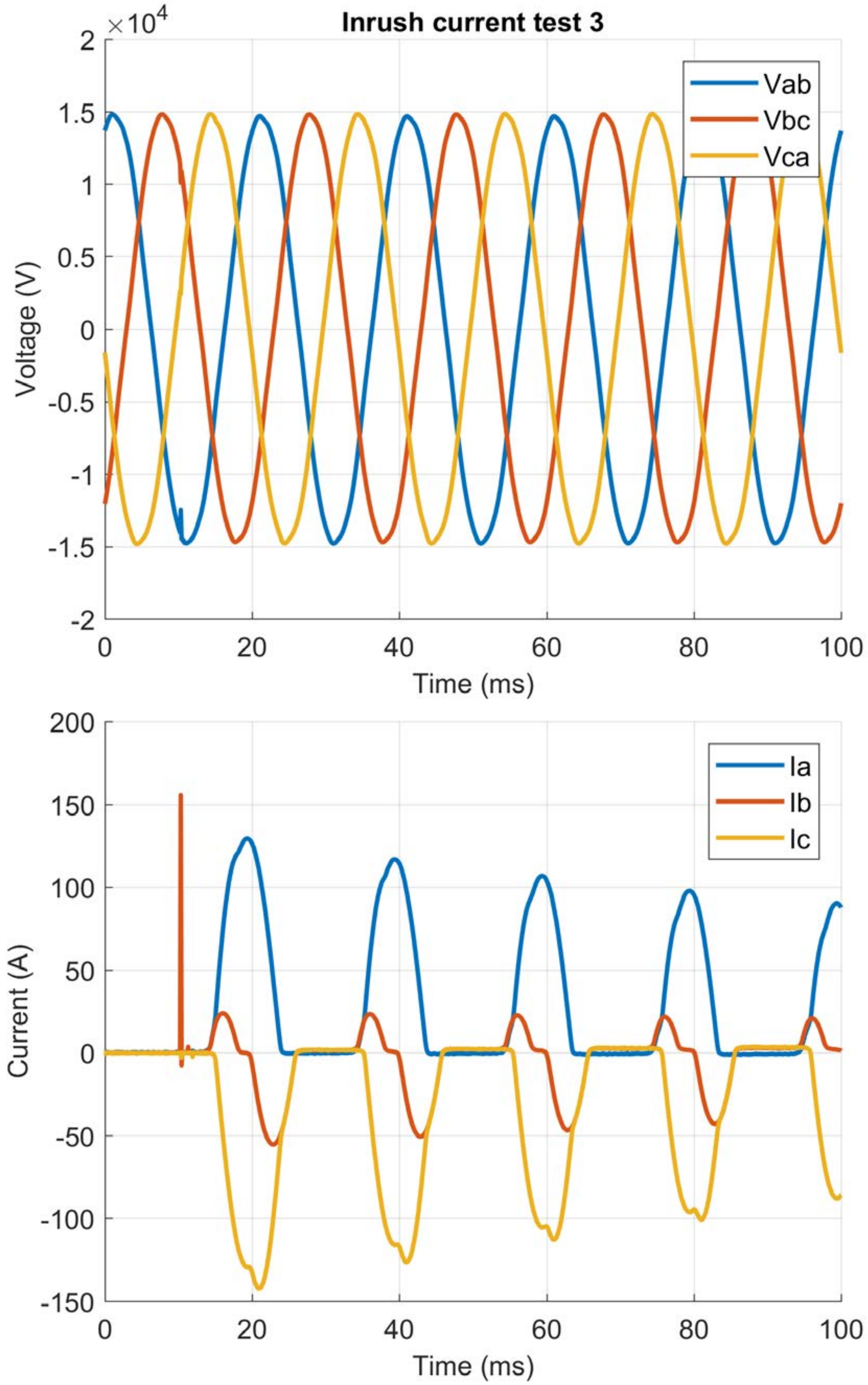


Figure 15 Transformer inrush test without inrush limiter (test3)

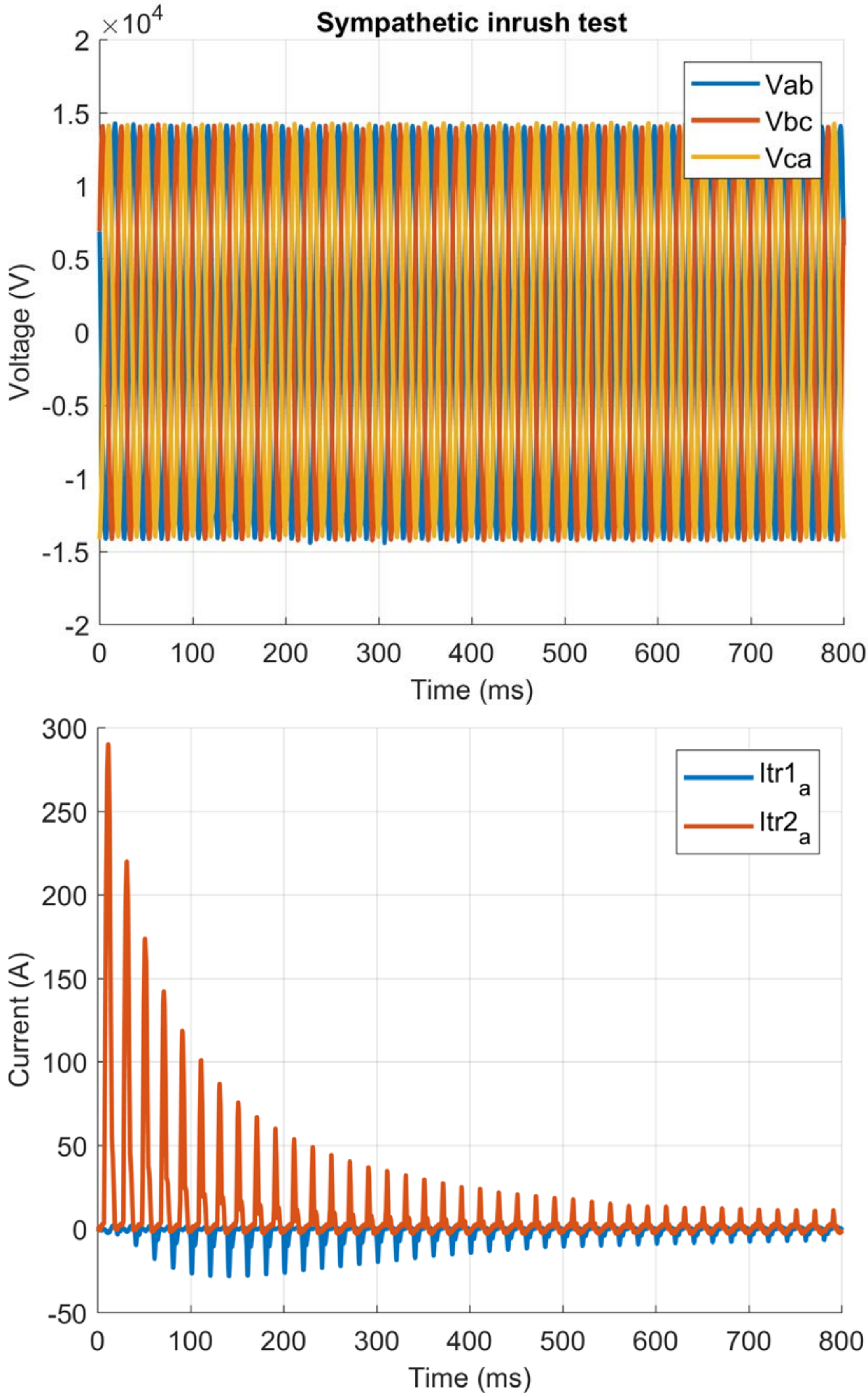


Figure 16 Sympathetic inrush test

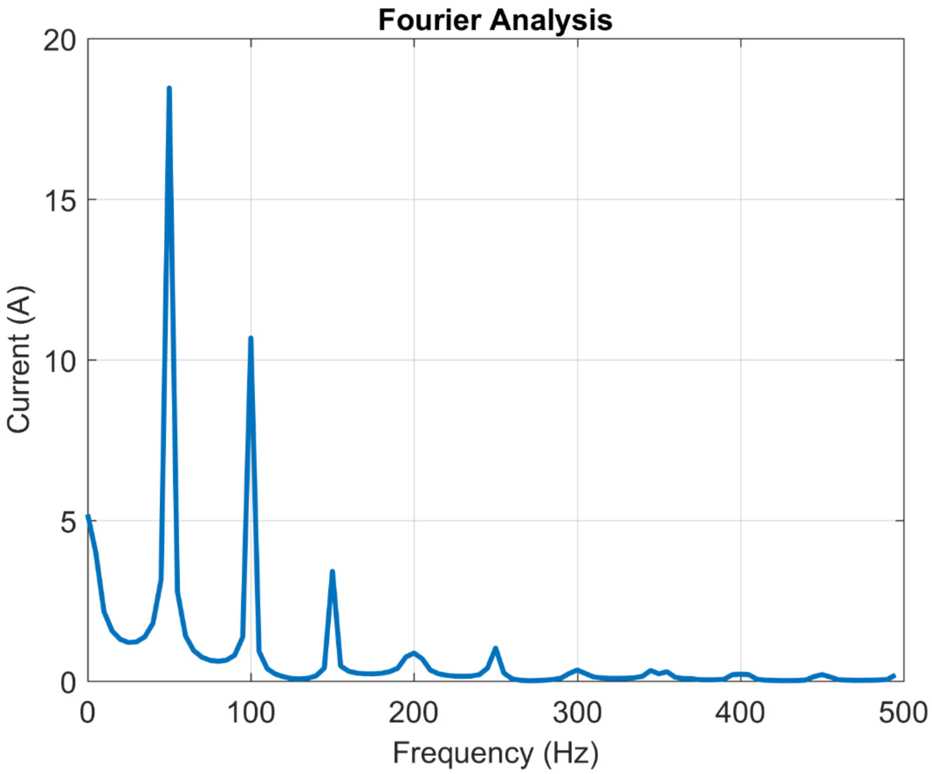


Figure 17 Fourier analysis of the sympathetic inrush current

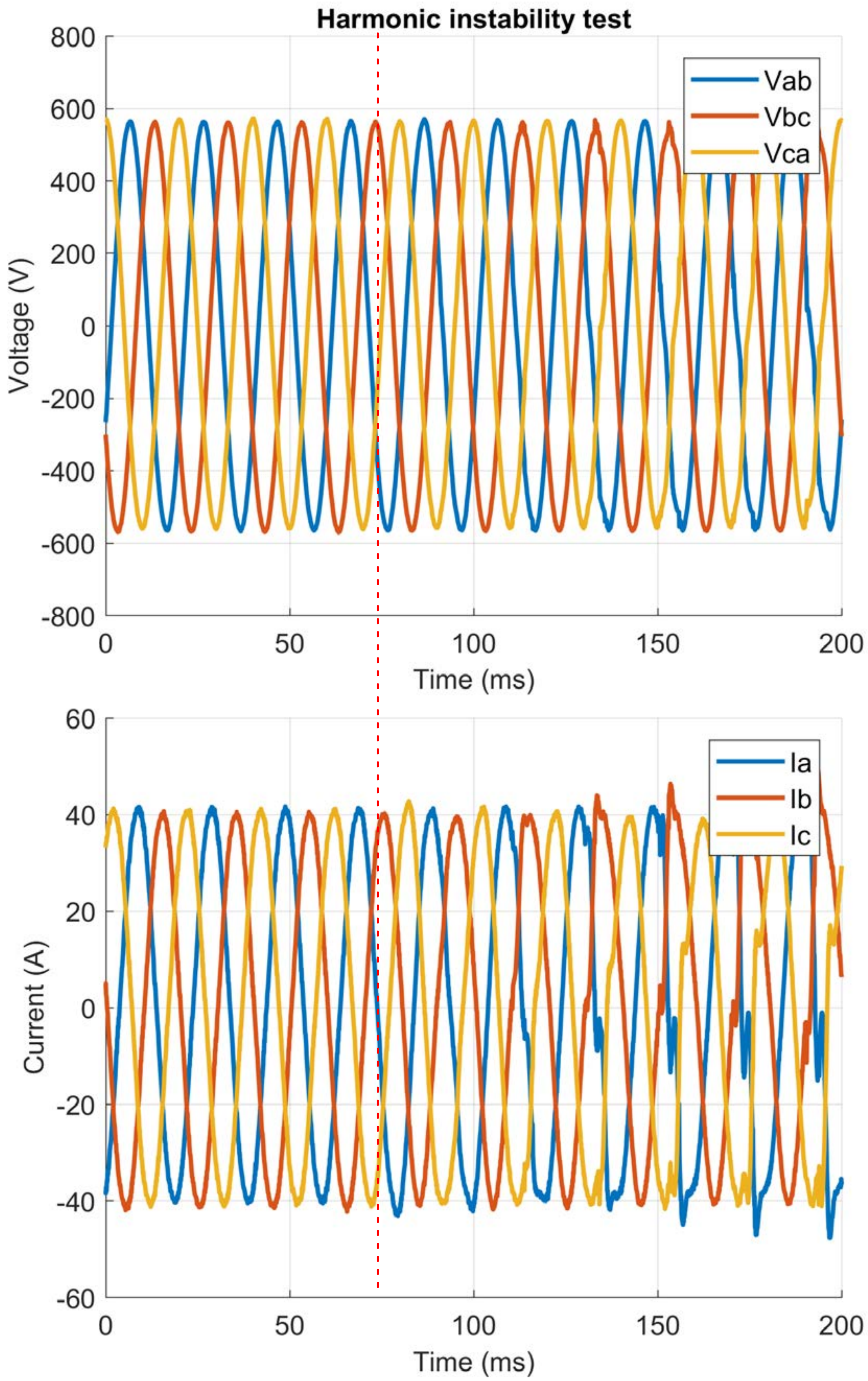


Figure 18 Harmonic instability test

6 Open Issues and Suggestions for Improvements

In order to mimic the inductive impedance in the HIL, the derivation of the output current of Egston power amplifier should be used to control its output voltage. As a result, the noises in the sensed current signals can be amplified and results in distortions in the voltage and current waveforms. Moreover, control delay in the Opal-RT system can cause the resonances between two GMPAs in the high-frequency range, which cannot fully mimic the dynamic interactions of the simulated system.

For the first issue, it is suggested that low pass filter is added to attenuate the high frequency noised in the sensed current signals, but this method is only recommended for the case where low-frequency dynamic behaviors of the power electronic converters is of concern, since the dynamic behavior of the power amplifier can be greatly affected by the low pass filter.

For the second issue, it is recommended to load the model in the FPGA. With parallel FPGA computation, the digital control delay can be greatly reduced.

7 Dissemination Planning

“Harmonic state-space model of converter transformer during the inrush condition for the harmonic instability assessment in the offshore wind farm” Conference paper to IEEE International Power Electronics and Application Conference and Exposition (PEAC) 2018

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