What’s the Rush 2.0

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Abstract— **The increasing penetration of Inverter Based Resources (IBRs) in the grid requires us to reconsider many previous firmly held assumptions that, if left unchallenged, could result in problems such as misoperation, equipment damage, and unnecessary re-work. One assumption often made in protective relay design involves the typical response of transformers to energization events. In a rotating machine dominated grid, transformers will experience between 8 and 12 times their rated current when energized. During this brief period there is a large percentage of second and fourth harmonics present in the current wave form. During this brief period there is a large percentage of second and fourth harmonics present in the current wave form. As power grids evolve to integrate increased penetration of IBRs, this behavior is no longer guaranteed. As a result, unexpected behavior during and after energization could cause misoperation of protective relays.**

This paper provides a follow-up to our previous paper, *“What’s the Rush? Can IBRs Handle Inrush Like Rotating Machines?”* In that paper we studied the effects of inverter-based resources (IBRs) on transformer energization that could impact the performance of relaying. Using an EMT software, multiple vendor-specific inverter models were simulated as they were switched onto a transformer to model energization under various conditions of grid strength and IBR concentration. We found that, while no potential challenges to distance or overcurrent relays were detected, issues such as a persistent second and fifth harmonic content and inrush current could affect the performance of differential relays.

Traditionally, second and fourth harmonics are used to discriminate between inrush and fault current. When IBRs are present in a sufficient quantity, they can generate a significant persistent second harmonic signal. This can impede recognizing that signature, which was traditionally known to be only generated during transformer inrush. Experimentation will be done to determine if traditional protective methods can still be effective.

The primary focus of this follow-up paper is to recreate the behavior of a typical grid. Using an electromagnetic transients modeling program, inverter setpoints will be modified to bring inverter outputs close to values typically seen in a rotating machine-based grid. The resulting simulation outputs will be tested with differential and overcurrent relays using a relay test set. If the inverter output is not able to be modified to achieve this goal, further testing will be performed with modified relay settings that can accommodate the harmonic nature of IBRs. These experiments will focus on test relay operating in the presence of persistent second harmonics, fifth harmonics, and inrush currents that exist after modifying inverter setpoints. We will evaluate the effects of long-lasting inrush on the dependability of second harmonic inrush blocking, the security of fifth harmonic overexcitation blocking, and the operation of the differential element. Our goal in these evaluations is to find a balance between security, sensitivity, and dependability.

I. INTRODUCTION

In this paper, we investigate the findings from our previous study, *“What’s the Rush? Can IBRs Handle Inrush Like Rotating Machines?”* [1] (WTR 1.0). Their findings indicate that inverter-based resources (IBR) could create an inrush event that will not fully decay as a rotating machine. This may leave residual current containing high-harmonic content even after the inrush event has subsided. This led the authors to question if the phenomenon would lead to problems with conventional transformer protection. The difficulties could manifest in a few ways. First, it is possible that the residual current would interfere with a relay's ability to successfully detect inrush due to unusual harmonic content, resulting in a nuisance trip. Second, if a fault occurs on a transformer in an IBR-dominated system, the residual current could inadvertently cause the relay to delay or block a trip. In this paper, many of the simulations from WTR 1.0 were recreated. Results from those simulations were then tested in a transformer protection relay. Testing was done using conventional protection settings to determine if the traditional philosophy of protection would need to be changed due to increased IBR penetration of the grid.

II. MODEL CREATION

The models used in this paper are based on the models from WTR 1.0. The original models used various sources to energize a 100 MVA autotransformer. Sources were connected to the high side of the transformer, and nothing was connected to the low side or tertiary. The transformer's high-side voltage was 230 kV, and the low-side voltage was 115 kV. A circuit breaker was placed between the transformer and the source. This allowed the model to initialize for 4 seconds before the breaker closed to energize the transformer.

This paper added a few updates to allow a clearer picture of the transformer during inrush and fault conditions. For each model, the runtime of the simulation was extended to 20s. Additionally, a 100 MVA load at 0.85 pf was added behind a breaker on the 115 kV side of the transformer. This load closes in 10s after the inception of the inrush event, giving some time for the inrush to decay. Finally, a close-in SLG fault was placed on the 115 kV side of the transformer, initiated 4 seconds after loading.

We examined several scenarios from WTR 1.0. We chose the scenario involving the inverter causing the most residual current. We examined three grid-forming and three grid-following cases involving that inverter. We also altered a rotating machine case to be a 500 MVA source with a 0.15 p.u. <88° impedance. In addition, two new scenarios were introduced. In the first, 30 IBRs were added in parallel to the grid-forming case, allowing examination of how a group of inverters will interact together. In the second, a fault was introduced shortly after inrush inception to get a clearer idea of how inrush will influence fault detection.

In the scenario 1, Fig.1, we investigate a 500 MVA synchronous source.

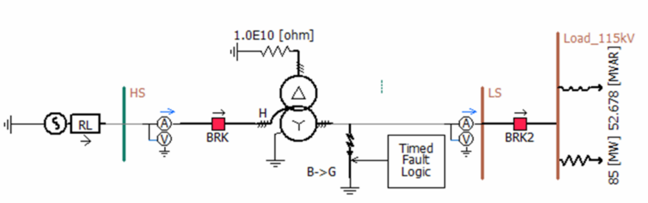

Fig 1. Model of Rotating Machine (500MVA, 0.15 p.u.<88° Impedance)

In scenarios 2-4, Fig. 2, we add a grid following inverter model with 100, 500, and 1000 MVA capacities. The rotating machine is the same as that in Scenario 1. This is a representation of partial IBR penetration.

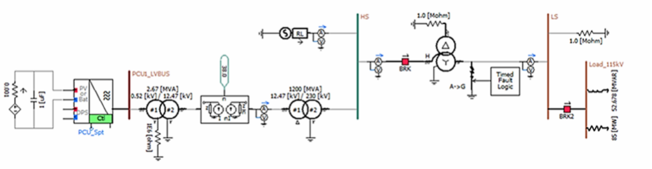

Fig 2. Model of Grid-Following Inverter (100MVA Case)

Scenarios 5-7, Fig. 3, remove the synchronous machine entirely in favor of a grid-forming inverter model with 100, 500, and 1000MVA capacities. This is a representation of full IBR penetration.

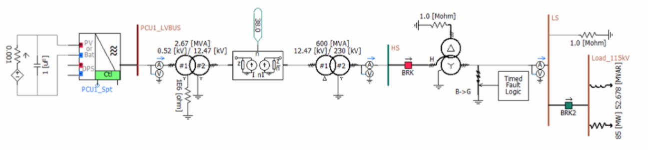

Fig 3. Model of Grid-Forming Inverter (500MVA Case)

Scenario 8, Fig.4, we replaced the single IBR from the 500 MVA grid forming case, with 30 IBRs, Fig. 5. Having many inverters in parallel gave us a more accurate simulation of the grid.

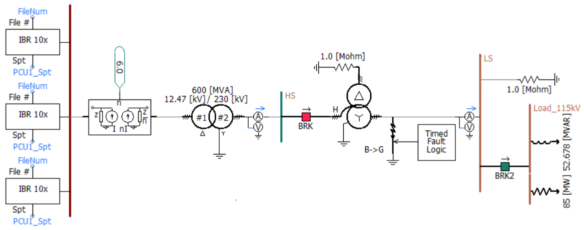

Fig 4. Model of Grid Forming (500 MVA 30 IBR Case)

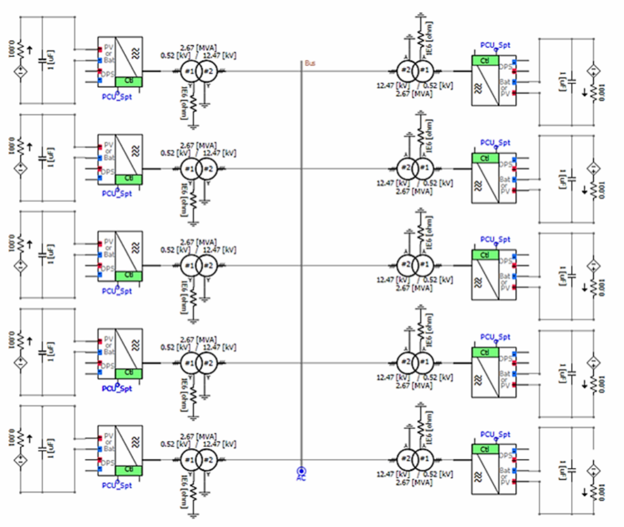

Fig 5. Model of Grid Forming (500 MVA 30 IBR Case)

Scenario 9 is a recreation of Scenario 6, but the fault is initiated 100 ms after the inception of the inrush event. This provides the ability to test if inrush will interfere with fault detection.

III. SIMULATION / TESTING

All scenarios were evaluated using an electromagnetic transient (EMT) simulation for a detailed examination of currents over small time increments. The power source (IBR and/or rotating machine) is connected to the same transformer and load in each scenario. Since the rating of the transformer (100 MVA) is larger than the output of a single IBR (2.6 MVA), a multiplication block that multiplies the output was used for the inverters. This allows a single inverter to be scaled up enough to match the transformer's power rating. This block multiplies the inverter 38 times for the 100 MVA case, 190 times for the 500 MVA case, and 380 for the 1000 MVA case. Scenario 8 was run with 30 IBRs in parallel, so a multiplier of 6 was used.

For each simulation, the currents flowing into and out of the transformer were recorded and stored in a COMTRADE file, which can be played directly to the relay using a relay test set. The output of the test set was scaled by a ratio of 800:1 for the low-side current and 400:1 for the high-side current. These ratios were chosen because they are commonly used in substations and sufficiently limited current during the fault to within the relay's specifications.

The test relay was configured to issue a trip solely on differential elements, with the desired behavior being the relay blocking a differential trip during the inrush event. The device would then issue a trip upon the detection of the fault. In addition, the relay was set to record 60 cycles of data if the current exceeded 150% of the nominal full load current. This allowed the relay to create an event during both the inrush and the fault. These events could then be examined in greater detail. Event waveforms are presented in Appendix A.

IV. RESULTS

As expected, in scenario 1 (Appendix A. Figures 6 & 7), the relay was able to identify the inrush and block tripping. It also successfully identified the fault and issued a trip signal. This result verified that the settings work as expected for a conventional system. In the following three scenarios, the relay successfully identified the inrush condition and tripped on the fault (Appendix A. Figures 8 & 9). Scenarios 5 through 7 (Appendix A. Figures 10 & 11) were of most concern in WTR 1.0. This is because a residual current continues to flow after the inrush condition has subsided. It was speculated that this could impact proper tripping on fault inception if the relay's harmonic restraint function never disengaged. However, that was not the case during testing. The relay was able to detect the fault and trip as expected. Scenario 8 was similar to Scenario 6 (500 MVA grid forming), except that 30 IBRs were simulated instead of just 1. This lowered the applied multiplier to make up the difference between the IBR output and the transformer size. In this scenario, there was less residual current, indicating a high multiplier may be responsible for some residual current. Testing Scenario 8 (Appendix A. Figures 12 & 13) produced the same responses in the relay as the previous three scenarios. The relay correctly issued blocking during inrush conditions while tripping for a fault. Finally, in Scenario 9 (Appendix A. Figure 14), to test the relay's response to a faulted system (that had not yet reached a steady state), a fault was placed 100 ms after the inception of inrush, with all other timing being the same as Scenario 6. In this case, the relay could still block at the beginning of the inrush, then unblock and trip for the fault.

The harmonic content was consistent across the three-generation profiles and only changed slightly in the 30 IBR case (Shown in Appendix B). Typically, harmonic blocking will utilize only the 2nd and 4th harmonics to provide security for inrush conditions. The behavior of the 1st, 2nd, and 4th harmonics during the synchronous, grid following, and grid forming cases all, largely, exhibited the same general behavior. 1st and 2nd harmonics peaked at the moment of inrush, then exponentially decayed to a nonzero steady-state value over approximately 5 seconds. The 4th harmonic had a slight "bounce" in the first half-second following inrush, where the 4th harmonic content peaks at the moment of inrush, and decays in a much more linear manner to near zero in around ½- second. The 4th harmonic rebounds almost to its peak before decaying, consistent with the 1st and 2nd harmonics. The most significant observed difference was the relative speed of the grid-forming cases (Appendix B. Figure 17). They exhibit the same behavior as the synchronous and grid-following cases but reach a higher steady state current in all observed harmonics. The decay was almost 3 seconds faster than the synchronous machine and grid-following cases (Appendix B. Figures 15 & 16). This phenomenon is likely due to the system's lack of a synchronous generator, which provides a larger resistance against the rate of change of frequency and voltage in the event of both inrush and faults. Additionally, in the 30 IBR, grid-forming case the 4th harmonic did not have the same "bounce" as all other cases. There was a slight decrease in 4th harmonic magnitude after the initial inrush, the same peak as the other cases, and the same attenuation, however it never had the same linear decrease to 0 Amps present in the other cases.

V. CONCLUSION

During testing, we discovered that a residual current after inrush for IBRs did not prevent the relay from operating appropriately during fault conditions. By increasing the number of IBRs, there was less residual current than with a single IBR. Some residual current may be due to the multiplier block used to boost the power of the IBR. This may also be due to the interaction of the IBRs. In either case, testing one IBR and relay combination provides insight but is not conclusive. It appears that, at least in this situation, conventional protection settings are adequate.

VI. FUTURE CONSIDERATIONS

Based on our simulations the exact cause of the residual current after transformer inrush could not be determined. It is advisable to perform physical testing to determine if this is an artifact of the simulation. This paper only investigated a 2nd harmonic blocking differential scheme. Further research into other protection schemes would be useful to determine if any are vulnerable to high IBR penetration. Repeating the same cases on a smaller capacity transformer would also allow for a grid-forming scenario in which the multiplier block could be eliminated. The EMT software only allowed up to 30 individual inverter units before it failed to compile, which still required using the multiplier block to deliver adequate power to the transformer. Simulating 30 inverters is also time prohibitive. Decreasing both the size of the transformer and load would allow for grid-forming scenarios without the use of the multiplier block. Another possibility is to vary the size of the rotating machine in the grid-forming case to see how it would change the interaction with IBRs. Finally, testing other IBR and relay combinations would be greatly beneficial.

VII. REFERENCES

[1] S. Billaut, and A. Miles, "What's the Rush? Can IBRs Handle Inrush Like Rotating Machines?," CIGRE US National Committee 2022 Grid of the Future Symposium.

Sebastien C. Billaut P.E., is a consulting engineer at Commonwealth Associates. Mr. Billaut holds an MS in Mechanical and Electrical Engineering from ESTP in France. He has 31 years of utility-related engineering experience, setting protection relays and power system modeling. He is the patent author of microgrid fault management technology. He also co-authored a patent on substation battery life extension during station outages.

He actively participates in industry-wide microgrid, distribution, and transmission protection systems standards. He serves as Chair of the IEEE PSRC Working Group K29, D44, KTF33, and K52 and is a member of IEEE PSRC Main and Subcommittees D and K. He is currently contributing to IEEE 1547.x and IEEE 2800.x

Joseph Johnson P.E., is a seasoned electrical engineer, graduating from Michigan Technological University in 2015 with a Bachelor's degree in Electrical Engineering. Specializing in relay protection settings and system studies, Joseph's expertise spans voltages of up to 500kV, where he has devised intricate protection schemes for critical components including transmission lines, buses, transformers, feeders, and capacitors.

Since delving into inverter-based resources in 2020, Joseph has actively contributed to the development and optimization of five battery energy storage systems and four inverter-based collection systems, ranging from 150 to 500 MVA. With a passion for engineering and a knack for innovation, Joseph is dedicated to advancing renewable energy technologies and tackling complex challenges in the field.

Jacob Quinn E.I.T., was born in Lansing Michigan and received a B.S. in Electrical Engineering from the University of Michigan in Ann Arbor Michigan in 2021.

Since 2021, he has been an Electrical Engineer with Commonwealth Associates Inc., in Jackson, MI, USA, specializing in relay settings and grounding for transmission substations.

James Steele E.I.T., is a substation engineering at Commonwealth Associates. Mr. Steele has 2 years of utility experience. He graduated from Michigan Tech. with a Bachelor's in Mechanical Engineering and a Masters in Electrical Engineering. James' experience is in protection and control, with an emphasis in relay settings. James has completed many substation projects including those for data centers and solar farms. In addition to his design experience, he has 10 years of experience as a submarine electrician.

VIII. Appendix A

A. Synchronous Machine

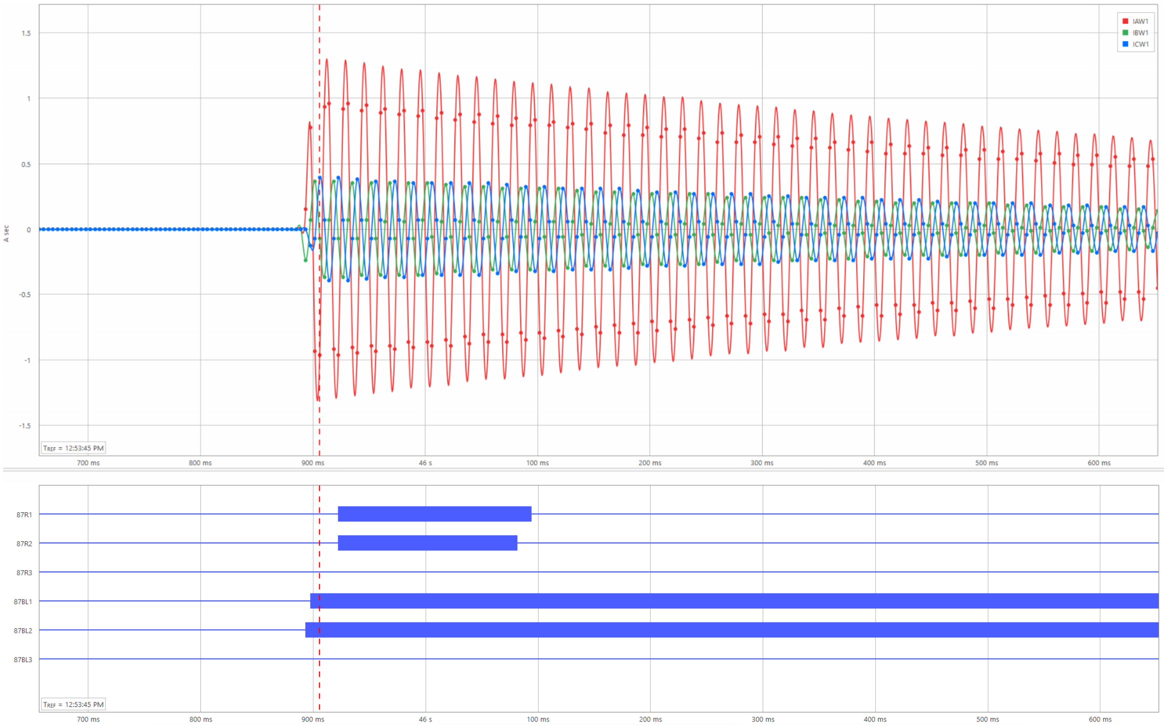

Fig 7. Synchronous Machine Inrush

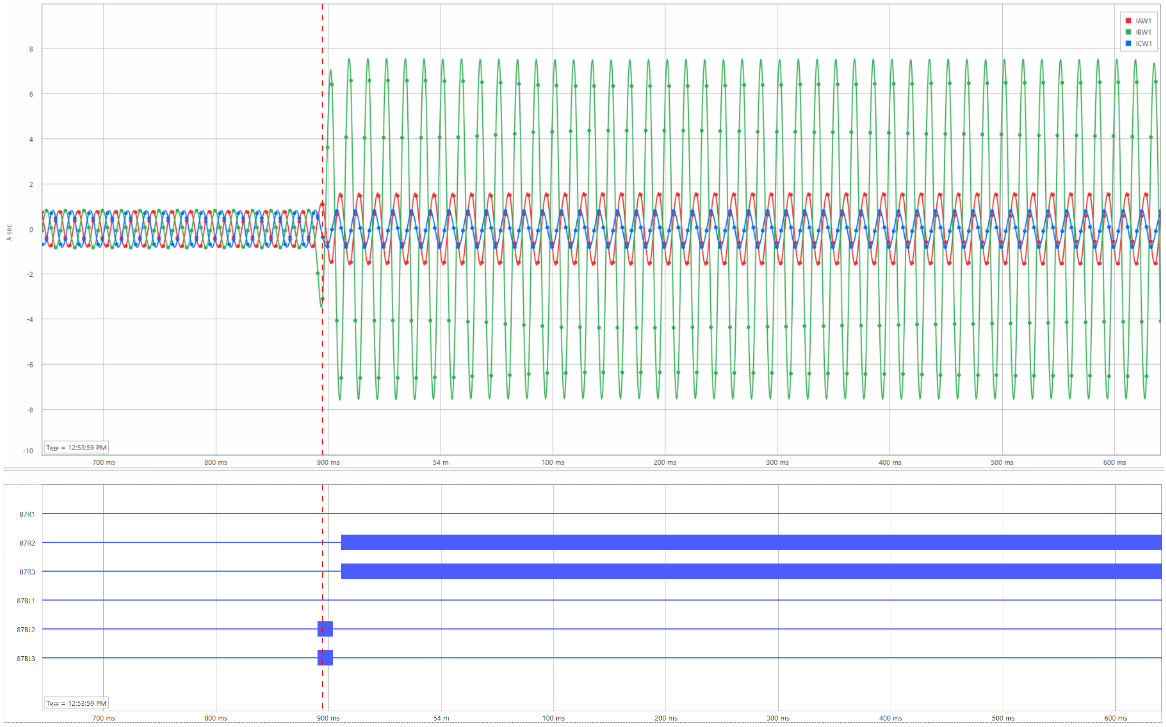

Fig 8. Synchronous Machine Fault

B. Grid Following – 500 MVA

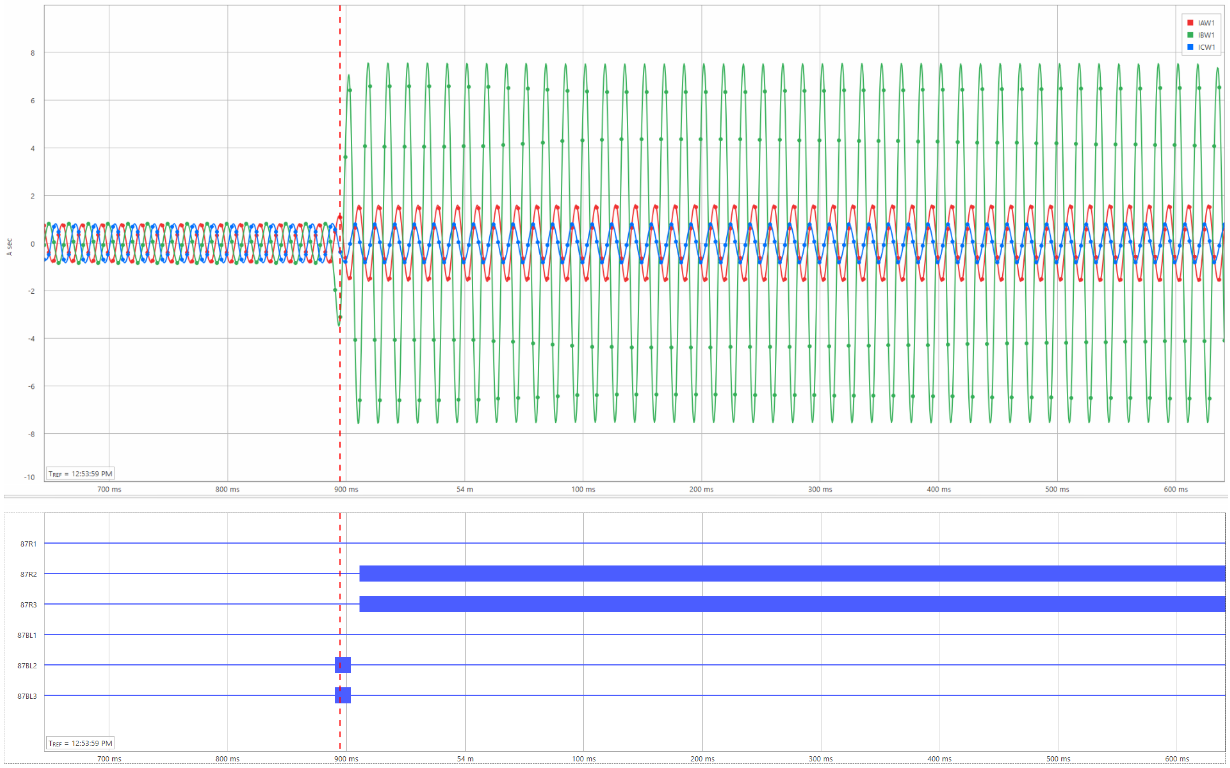

Fig 9. Synchronous Machine Fault Synchrowave File

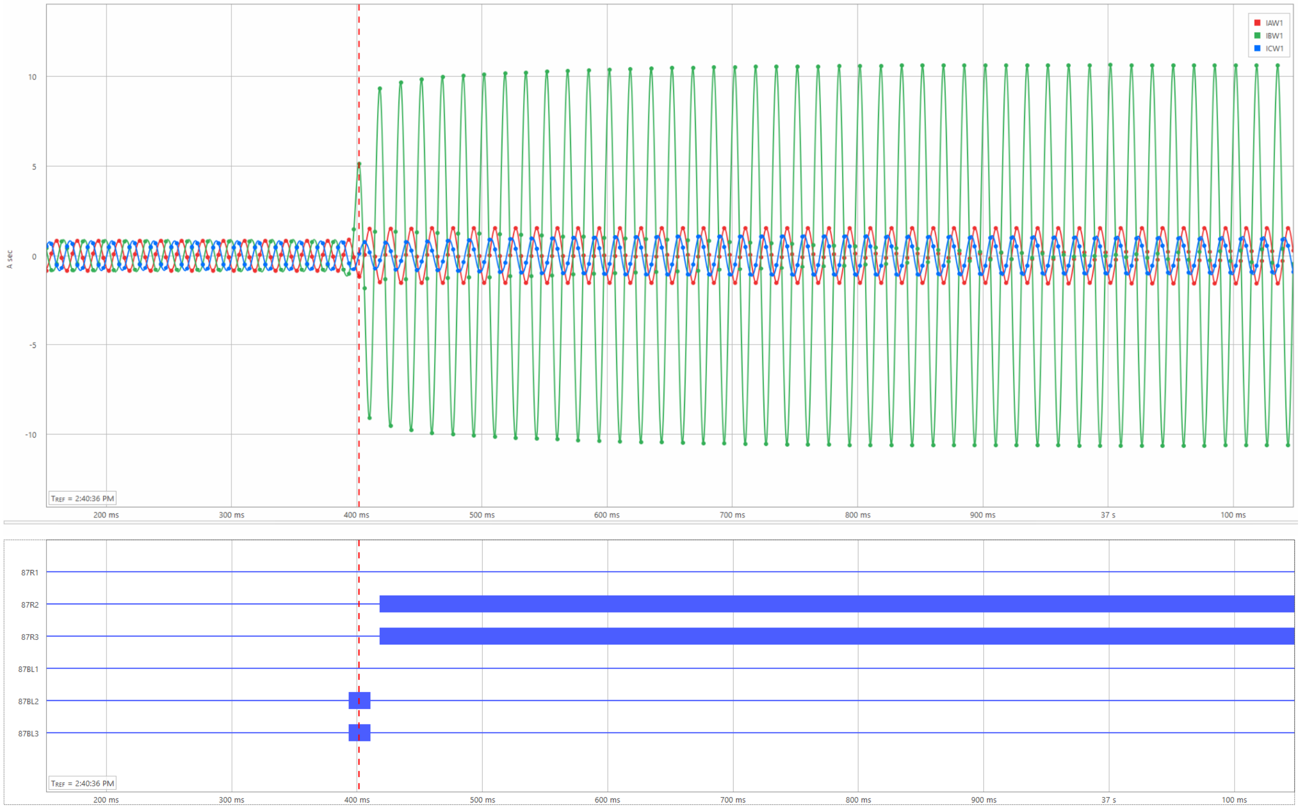

Fig 10. Grid Following Inverter (500MVA) Fault Synchrowave File

C. Grid Forming - 500 MVA

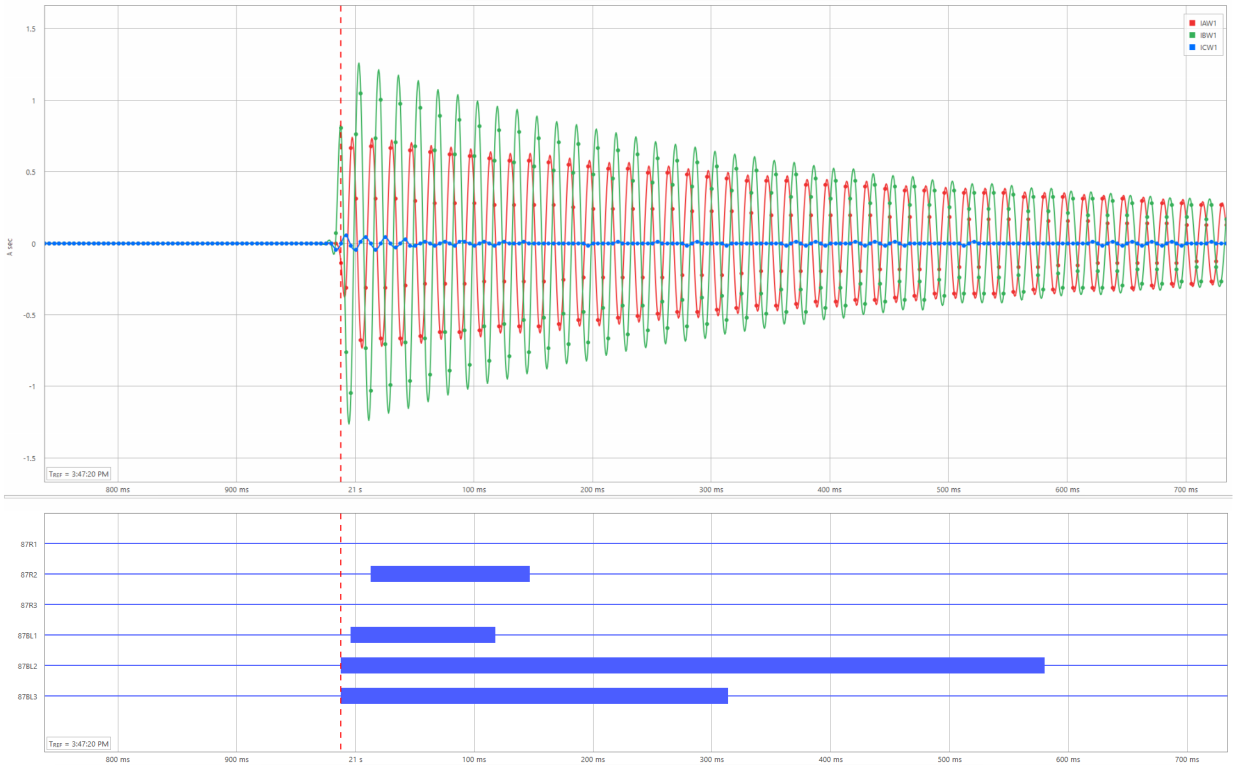

Fig 11. Grid Forming Inverter (500MVA) Inrush Synchrowave File

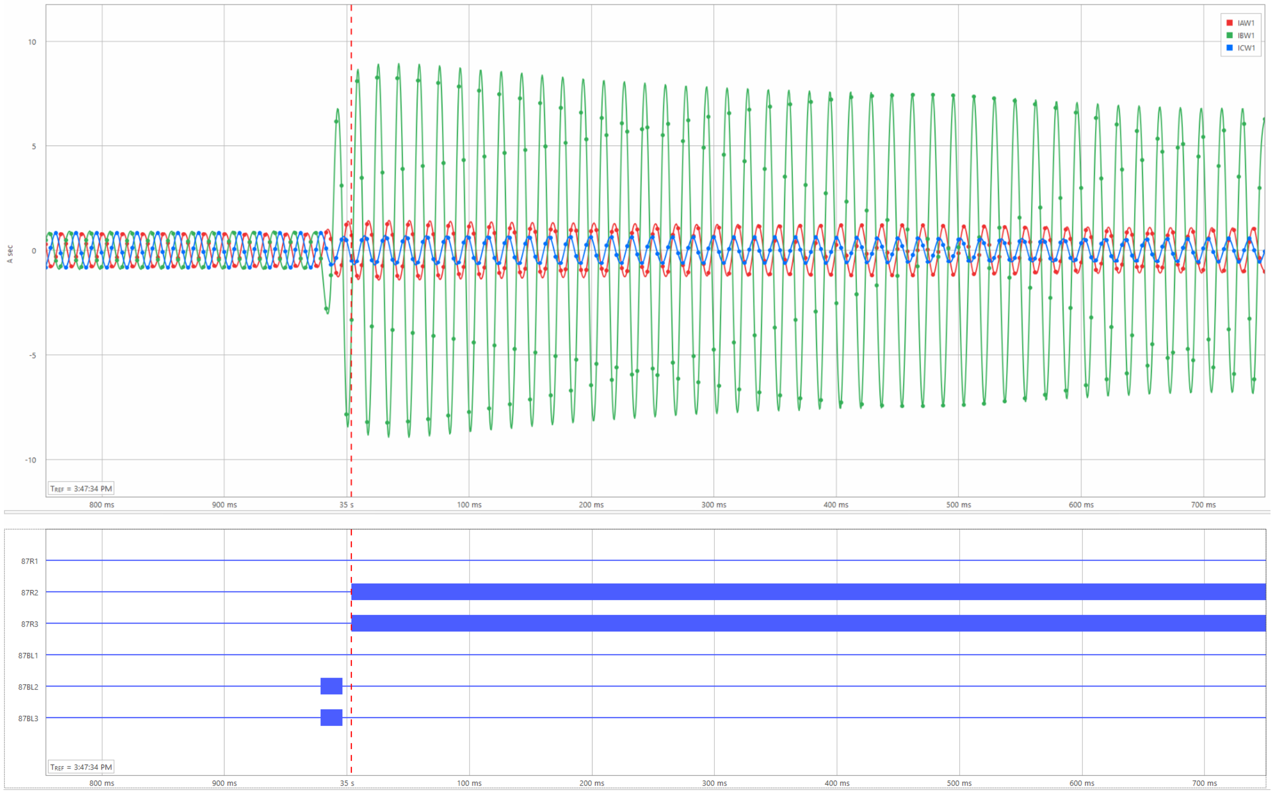

Fig 12. Grid Forming Inverter (500MVA) Fault Synchrowave File

D. Grid Forming – 30 IBRs

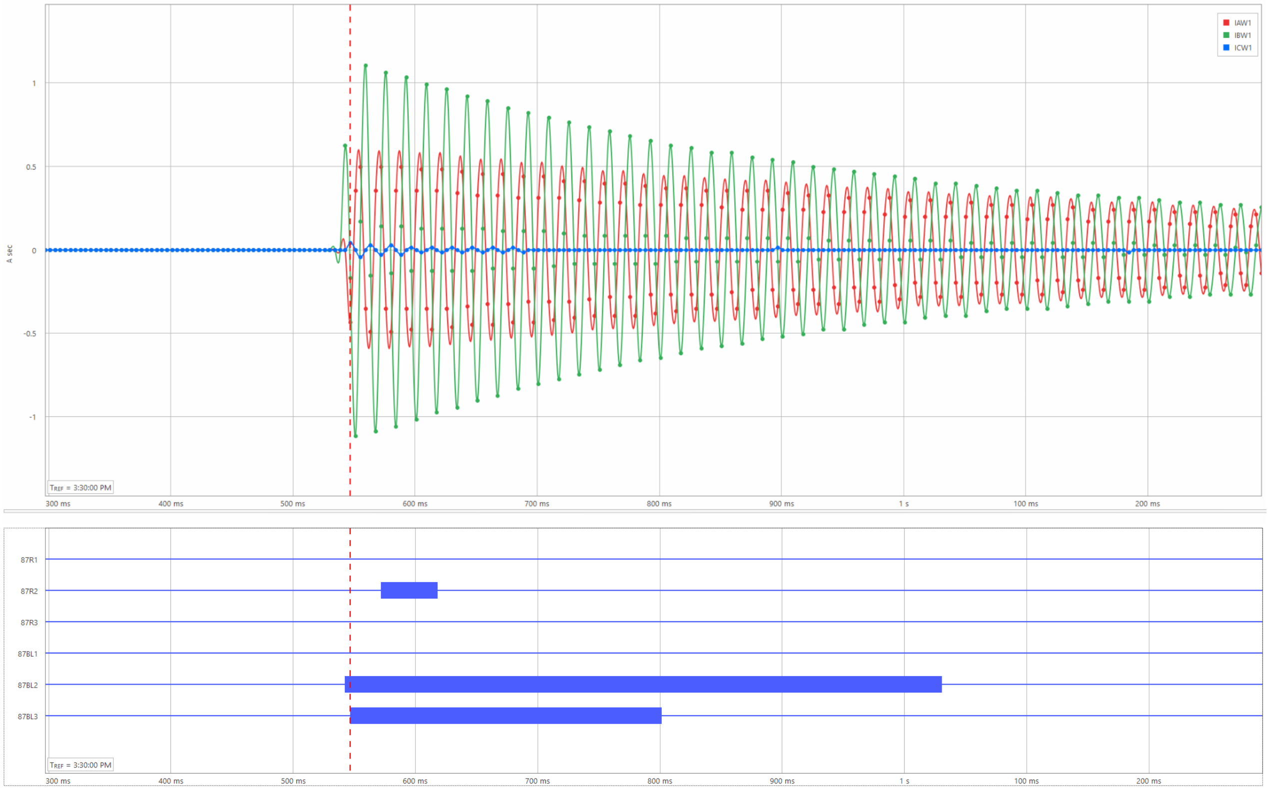

Fig 13. Grid Forming Inverter (500MVA – 30 units) Inrush Synchrowave File

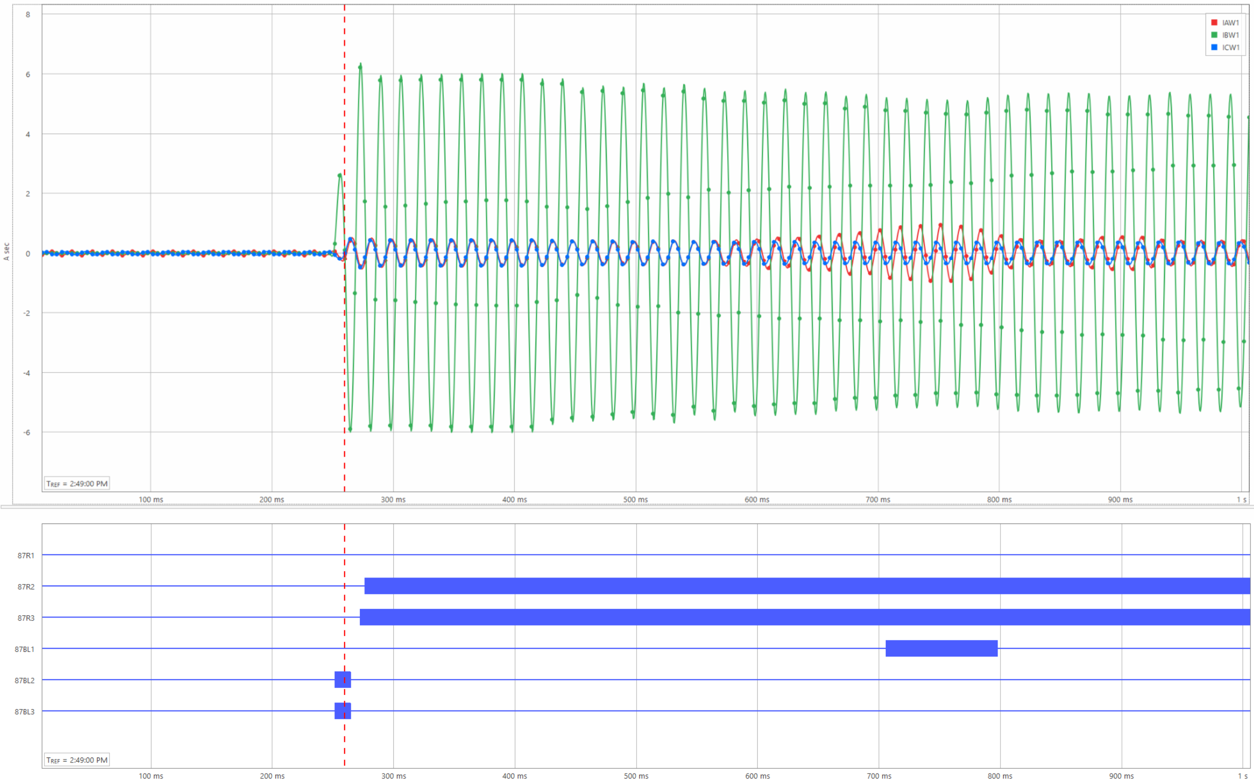

Fig 14. Grid Forming Inverter (500MVA – 30 units) Fault Synchrowave File

E. Grid Forming – Fault During Inrush (500 MVA)

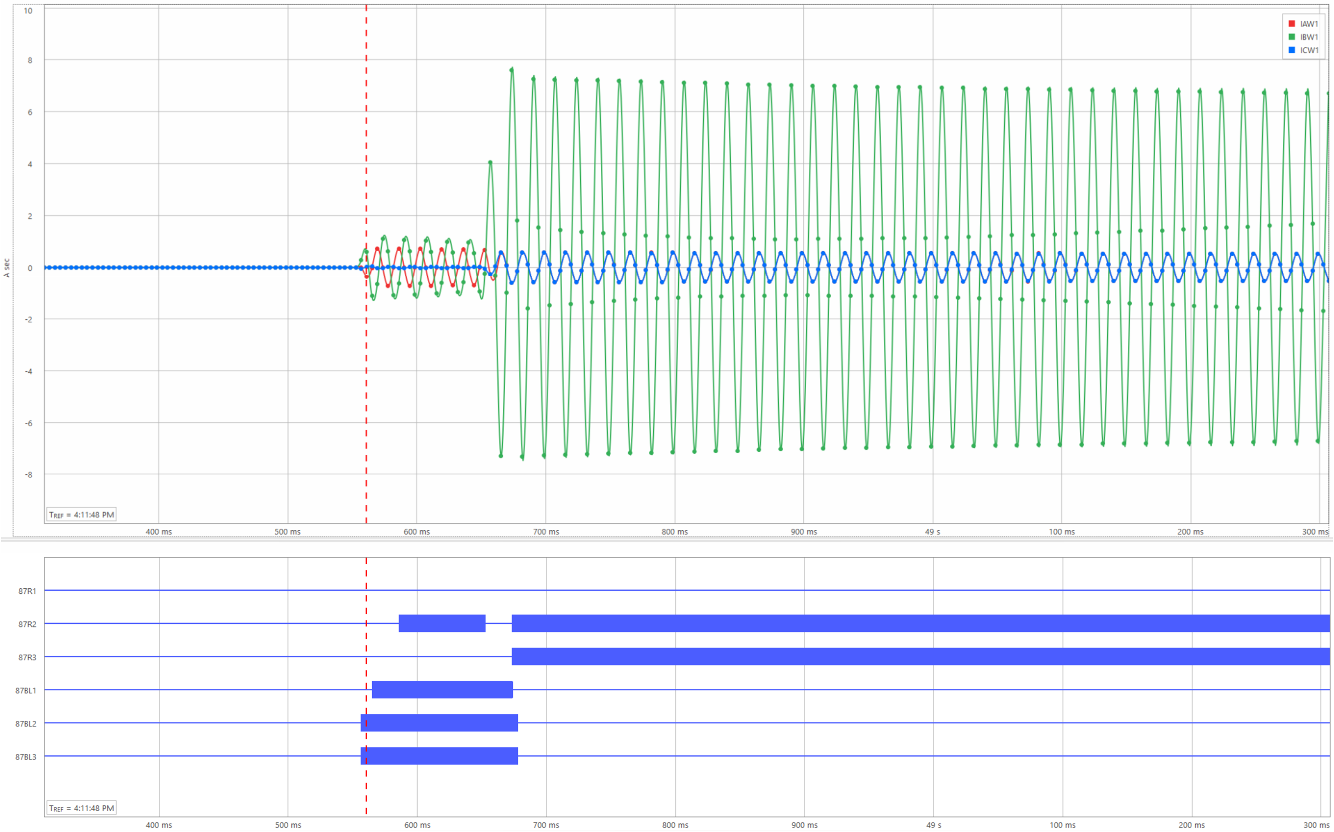

Fig 15. Grid Forming Inverter (500MVA) Fault during inrush Synchrowave File

IX. APPENDIX B: HARMONIC WAVEFORMS DURING INRUSH

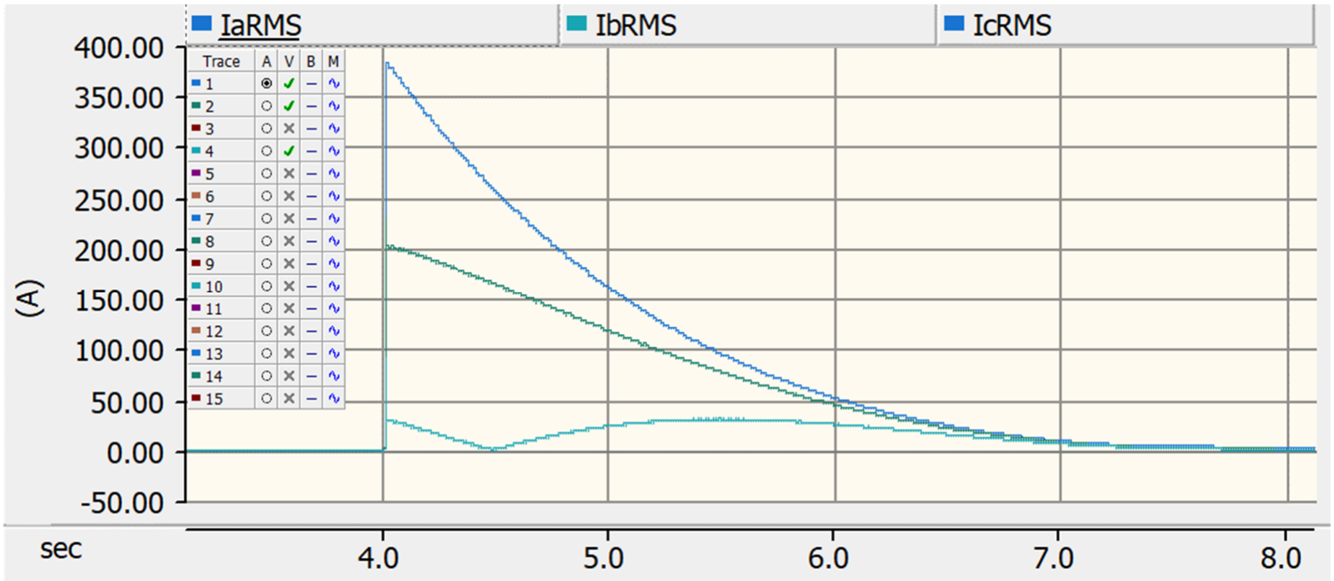

Fig 16. Synchronous Machine Inrush Harmonics

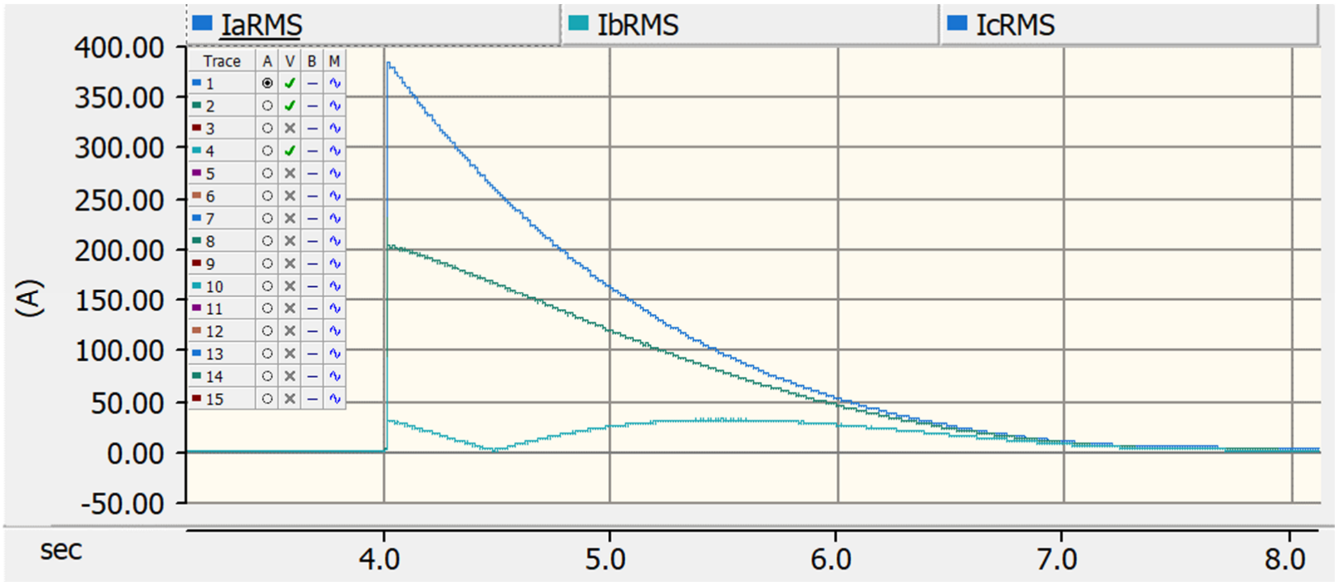

Fig 17. Synchronous Following Inrush Harmonics

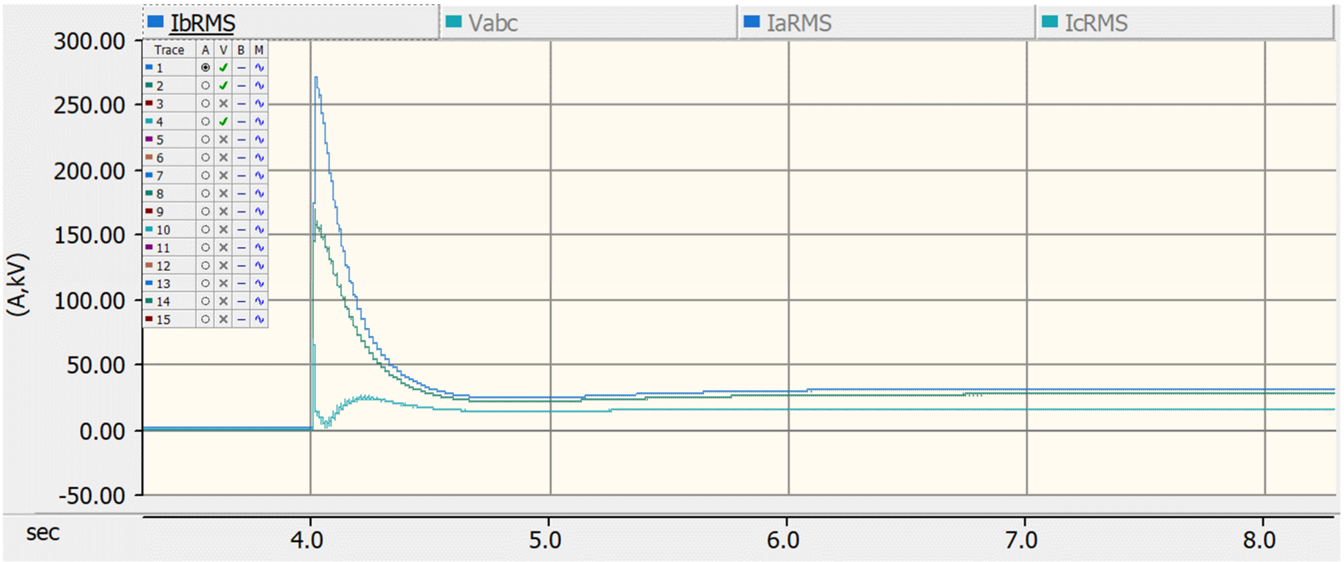

Fig 18. Grid Forming Inrush Harmonics

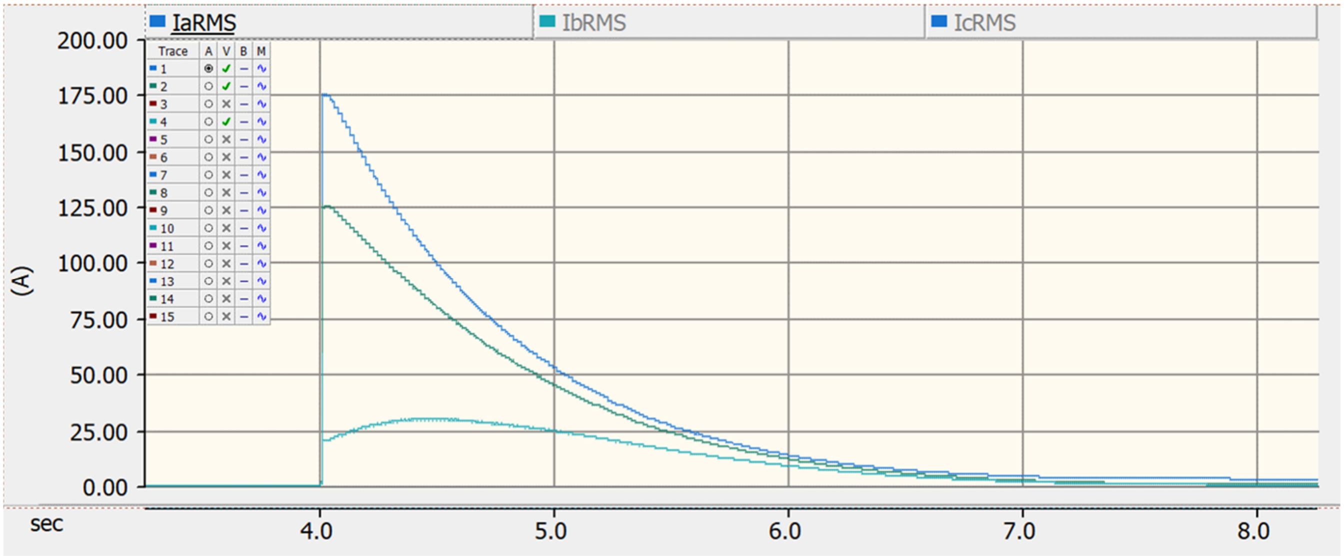

Fig 19. Grid Forming Inrush Harmonics (30 IBRs)