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What's the Rush? Can IBRs Handle Inrush Like Rotating Machines?

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SUMMARY

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 is in the typical response of transformers to energization events. It is understood that transformers energized with a rotating machine-dominated grid will experience between 8 and 12 times their steady state current values in magnetizing current and, for a brief period, will have a high percentage of second and fourth harmonics. As power grids evolve to integrate increasingly elevated levels of IBRs, but this behavior is no longer guaranteed. As a result, unexpected inrush behavior during energization could cause misoperation of protective relays installed in the station.

In this paper the inrush of transformers in high penetration of inverters grids (dominated by IBRs and in microgrids) is analyzed to determine their response to energization, and to evaluate current industry best practice protection schemes. We model actual inverter models from different inverter manufacturers that are currently in service on the grid and with electromagnetic transient simulation software for utmost accuracy. We also estimate the impact of transformer design on results when transformer magnetic design characteristics are varied. The configuration of system source strength in reference to the transformer size is also varied to determine if the strength to transformer size ratio has an impact on the results. This consideration could help the system planner improve their interconnection requirement consideration. Under each case study, we will review whether harmonic inrush mitigation is still successful in securing the differential relays of a transformer that is energized. The results may indicate that adjustments to restrain and blocking are needed under such circumstances.

Lastly, the reader will learn if other transmission protection could be operating during the energization. We will evaluate phase and ground distance protection as well as phase and ground overcurrent protection. The inrush may appear as a remote bus fault, and if its effects do not quickly dissipate, the overreaching time delay and time inverse over-current element's security may be affected. This is because lower fault current characteristics will deepen the voltage drop under inrush, which in turn, could also lengthen the duration of the energization

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inrush condition. To verify the relay performance, we will test the COMTRADE export from the EMTP simulations on relays with various manufacturers and types. All the results will be characterized and cataloged in a tabular form with the intent to extract the threshold of applicability and settings preparation rules to help engineers with their project implementation. In summary, our paper evaluates how transformers respond to inrush in grids with major contributions from inverter-based resources. It analyzes the inrush characteristics for their impact on protection and operation practices using equipment modeling of real inverters.

KEYWORDS

IBR, Inrush, harmonics, energization, misoperation, relays, magnetic, transformer, simulations.

Background about Transformer Inrush

To illustrate the concept of transformer Inrush, we will use Figure 1 and Figure 2, where the blue curve is the Voltage at the terminal of the transformer; the red curve is the flux density B generated; the black curve is the B/H curve (hysteresis loop); H is the magnetic field strength which relates to the magnetizing current. Figure 1 illustrates operation once the switching transient has settled. Figure 2 is a representation of an energization inrush.

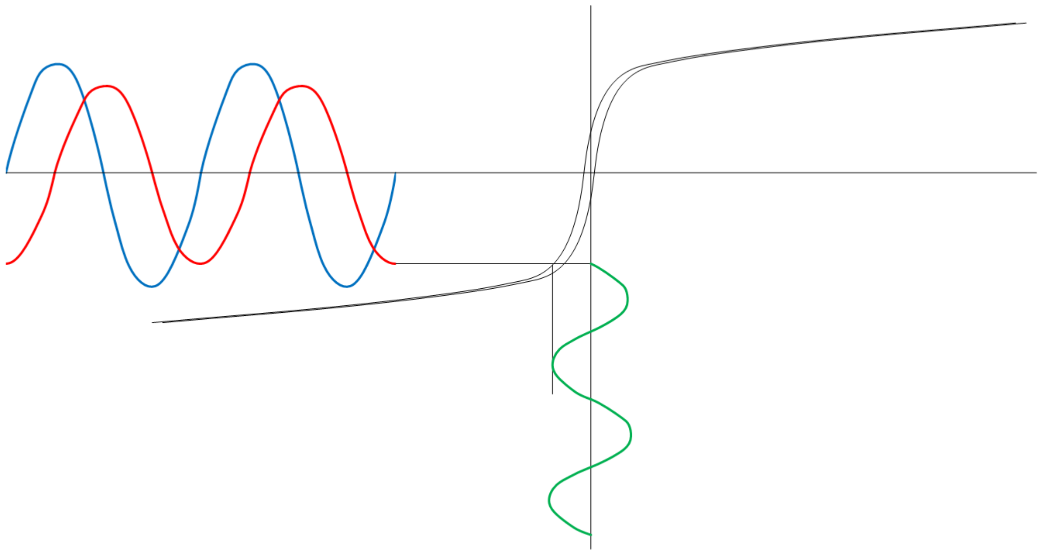


Figure 1. Y-axis Source voltage and Magnetic flux density, X-axis Excitation current

To understand electrically induced magnetism and transformer inrush, there are 3 main relationships to consider:

- Voltage relates to magnetic flux
- Flux density relates to magnetic field strength
- Magnetic field strength relates to current flow

These relations derive from the following physics equations and laws. This is due Ampere's Law

$$\oint B\,dl = \mu_0 I_{enc}$$

The integral path of the magnetic field around a closed loop is proportional to the current enclosed. This means that

$$\oint H\,dl \approx I$$

The magnetic field is proportional to the current flow.

In a vacuum B and H are perfectly proportional, in materials, particularly ferromagnetic materials, they are not exactly correlated.

Their relationship is defined by material dependent B/H curve. Ferromagnetic materials exposed to an increasingly strong magnetic field align their free electrons' spin progressively but with a lag. The lag in change is characterized by hysteresis between the magnetizing force and the magnetic induction. Once completely aligned in the material, the field can only strengthen outside of the material. This explains the 2 slopes in excitation curves.

During transformer energization, it is likely that the existing magnetization state will not align with the voltage point of wave. This creates a magnetization offset as shown in figure 2. For economical cost reasons, the core cross area is closely sized to match the maximum voltage excitation, by IEEE standards it is sized to be 110% based on the nominal voltage. The small excitation margin means that small offsets lead to reaching maximum material polarization quickly, and beyond that point in air or a vacuum, the magnetization current must be much greater to allow additional magnetic field increase.

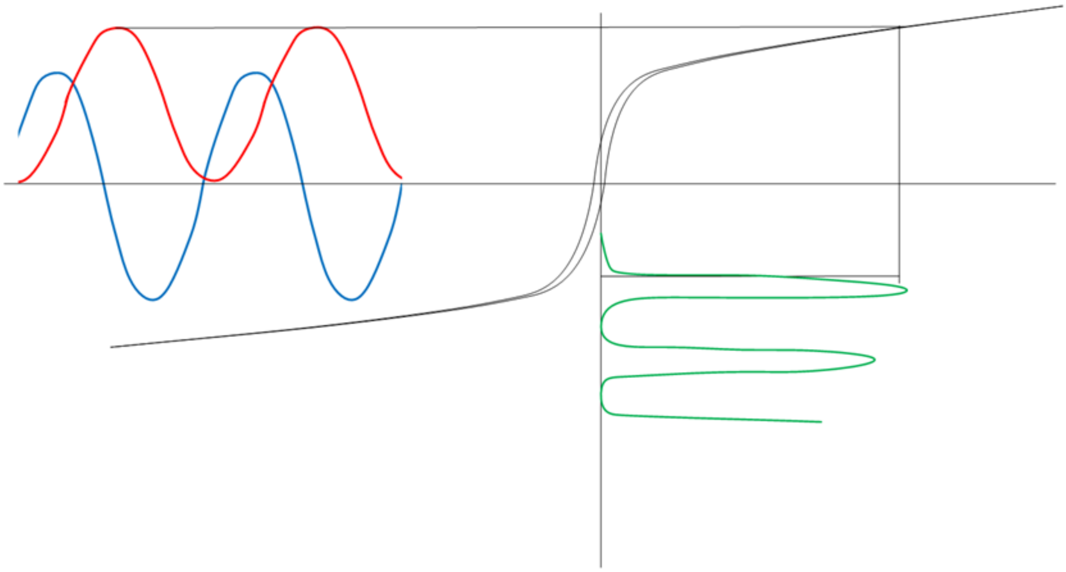


Figure 2.

Inrush currents can be large, typically 10 to 15, but in some circumstances up to 40 to 60 times the transformer self-cooled rating. The Inrush decay depends on the source energizing the transformer. More specifically, it depends on the source impedance X/R ratio. The larger it is the longer it will last.

The overall source impedance magnitude is also critical, as if it is too large in comparison to the inrush current and to the voltage applied, this can cause severe voltage drops at the point of service.

Background about Inverter Based Resources (IBR)

Synchronous generators have historically been the predominant means of power generation. This will most likely no longer be true within 15 to 30 years as they are being replaced by Inverter Based Resources (IBR).

The voltage and current output from IBRs are solely a result of the controls applied to the electronics gates, within the equipment's capabilities.

Synchronous generators on the contrary are built based on electromagnetic physics. This means that voltages and currents are a product of controls applied to their electromagnetic characteristics. The immediate states of current and voltages following a sudden change, switching, or faults are solely dependent on the electromagnetic characteristics.

This means that the response of a synchronous generator dominant system to a sudden change can be electrically solved through calculations. On the contrary, IBR's present a clear challenge to predict the behavior of the system when responding to a sudden change.

This unknown is principally due to the lack of standardization as well as proprietary algorithms. With disclosed and standard control algorithms, a sudden change response could be predicted. Inverter manufacturers protect their intellectual property by providing "black Box" EMTP models of their controls.

It is necessary to put them to the test to predict their response to sudden changes.

This paper will focus on transformer Inrush energization as the sudden change being studied. It is not intended to be an exhaustive investigation of all inverter controls as this is an ongoing and evolving response as new manufacturers come on the market or as they update their control firmware.

EMTP Modeling

Modeling for this paper requires accurate representation of inverter control systems, so an electromagnetic transient software is used. PSCAD is selected because of the readily available models from inverter manufacturers, and it is the software with which the authors of this paper are more familiar.

The goal of the simulations is to measure the response of different types of generation to the closing in of a transmission level autotransformer. There are four different scenarios considered:

1. Traditional rotating machinery dominated grid
2. High penetration of IBRs operating in grid-following mode (inverter #1)
3. IBR dominated grid operating in grid-forming mode (inverter #1)
4. High penetration of IBRs operating in grid-following mode (inverter #2)
5. IBR dominated grid operating in grid-forming mode (inverter #2)

Below is a figure showing the layout of each model.

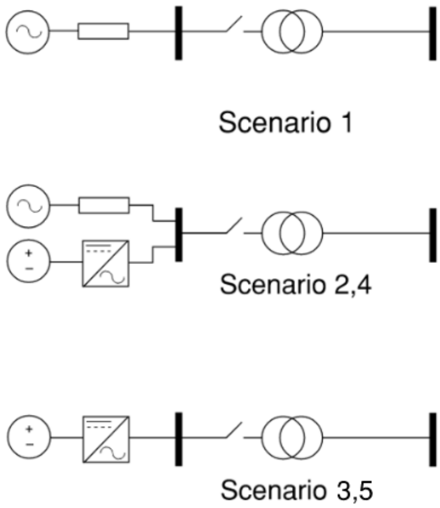


Figure 3. Model one-line diagrams.

The autotransformer to be energized will be the same in all five scenarios. This transformer is a 230/138 kV autotransformer with a buried 13 kV tertiary. It has a 7% primary to secondary impedance rating and the neutral point is solidly grounded. This transformer is representative of many transformers in the transmission network. Table 1. shows the transformer information in tabular form.

Table 1

Parameter	**Value**
MVA Rating	100 MVA
Primary Voltage	230 kV
Secondary Voltage	115 kV
Pri-Sec Leakage Reactance	8%

In addition to these parameters, additional saturation characteristics need to be specified in PSCAD for the software to simulate inrush correctly. These values are also typical of a transformer this size.

Table 2

Parameter	**Value**
Air Core Reactance	20%
Inrush Decay Time Constant	1 s
Knee Voltage	1.17 p.u.
Magnetizing Current	0.4 p.u.

Scenario 1

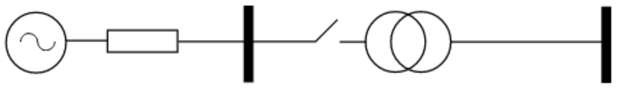


Figure 4.

In scenario 1, transformer inrush is modeled using a classical three phase voltage source behind an impedance. The voltage source is used to model a grid equivalent at the high side of the autotransformer. It has the following parameters:

Table 3

Parameter	**Value**
Base MVA	100 MVA
Base Voltage	230 kV
Impedance Type	R // L

This scenario is run with three different values of source impedance to simulate a weak, medium, and strong source equivalent. The three impedance values are shown below.

$$\begin{bmatrix} 0.1 \\ 1.0 \\ 10.0 \end{bmatrix} \angle 88^\circ \text{ p.u.} = \begin{bmatrix} 52.9 \\ 529 \\ 5290 \end{bmatrix} \angle 88^\circ \ \Omega$$

Scenario 2

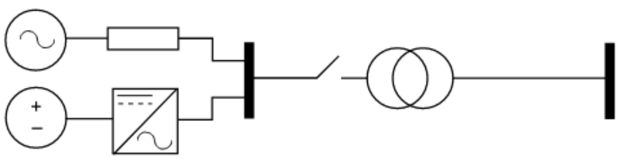


Figure 5.

Scenario 2 is similar to the weak source case in scenario 1 but has IBR generation in parallel with the grid equivalent. The IBR is operating in grid-following mode; it takes in power control setpoints for power targets and outputs current based on the voltage measured at its terminals to hit that target.

Due to the nature of the available inverter models, the inverter shown in Figure 6 is an equivalent of parallel inverters to meet the desired power output for the simulation. To measure the effect of output power before the transformer energization, three different cases will be studied: 100 MVA output from the inverters, 500 MVA output, and 1000 MVA output. Each of these outputs will have a power factor of 0.85.

Scenario 3

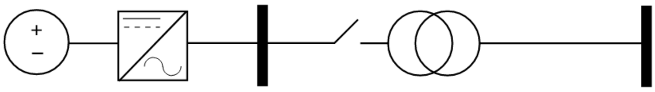


Figure 6.

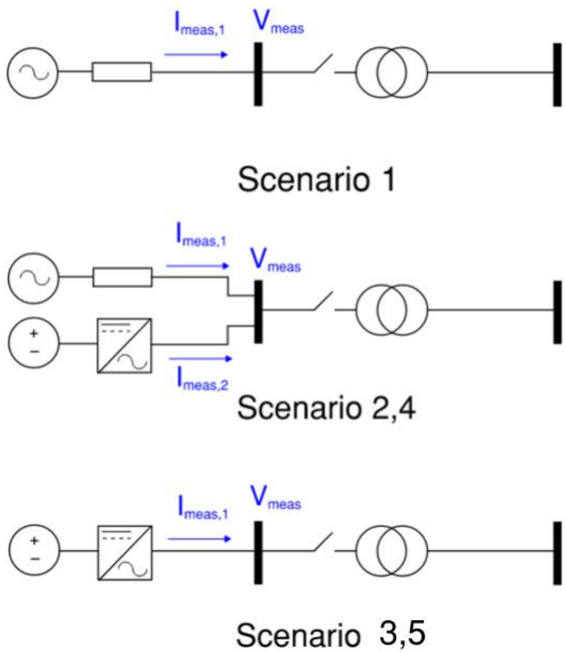
The last scenario is the case of IBR dominated grids. In this scenario, there is no voltage source generation. The inverter models are put into grid-forming mode and allowed to reach a steady state energizing the high side bus.

Scenario 4
Same as scenario 2 but with a different inverter manufacturer's model.

Scenario 5
Same as scenario 3 but with a different inverter manufacturer's model.

Procedure
In each of the scenarios above, the sources are given time to ramp up to a steady state. Once the high side bus is at rated voltage and the source output is constant, the switch to the autotransformer is closed. Switching occurs at the same point in each simulation for easier comparison of waveforms and to minimize differences due to point-on-wave switching.

Current measurements for each source are recorded for the entire simulation. Voltage measurements occur at the high side bus. For scenarios 1,3, and 5, there will only be one set of current measurements; for scenario 2 and 4, there will be two sets of current measurements. All simulations will only contain one set of voltage measurements. Measurement locations are shown in Figure 7.



Analysis of results

The analysis of the results of these cases is achieved by recording some key data for each of the cases. The peak Inrush current, the time to decay to 50% of the peak value and the time to decay to 10%. One important piece of information is related to the effect of the current inrush on the bus voltages, as this is what will be seen by other customers connected to the system. To investigate this, we recorded the maximum voltage drop as well as the duration of time below 0.95pu voltage.

While recording the data we quickly found that the inverter sources had large harmonic content appearing in the voltage. To allow readable voltage drop evaluation, we had to process the data with a 16-points cosine filter. Figure 8 illustrates this behavior, in the graph, the voltage signal in red is unfiltered, while the one in blue is filtered:

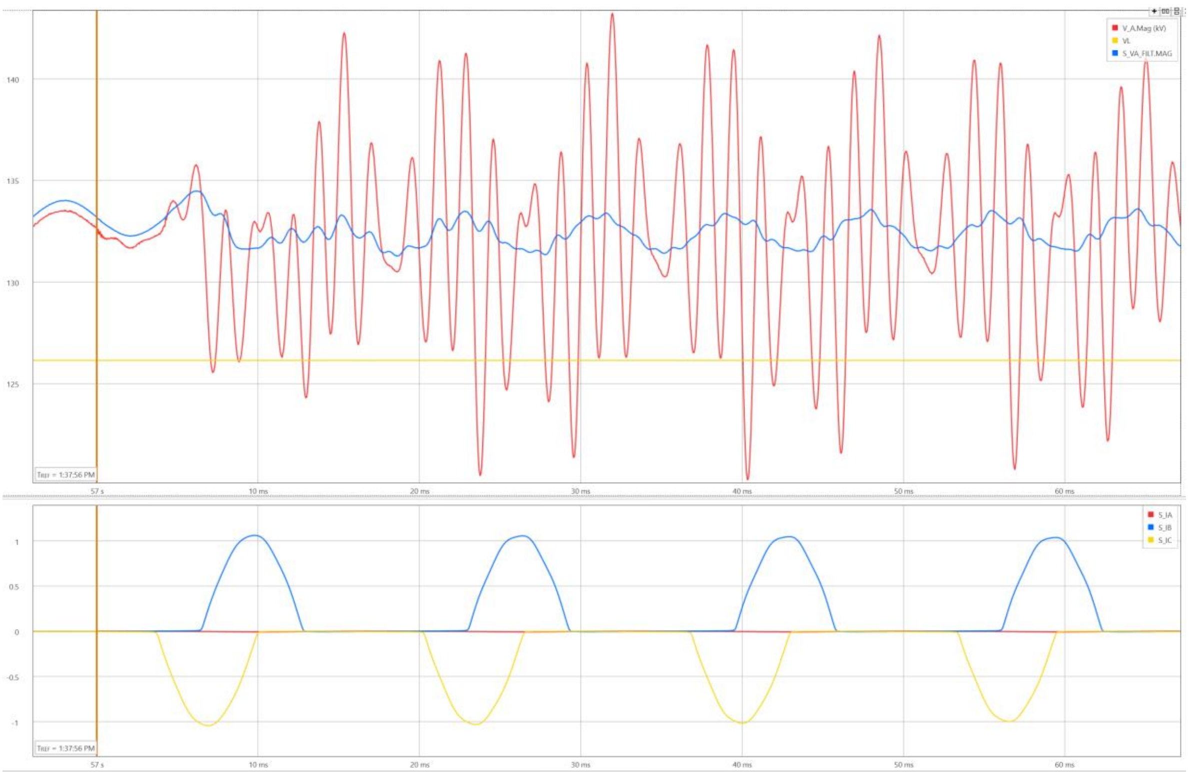


Figure 8. 1GW grid forming inverter with 100 MW transformer inrush

Findings

A. Inrush current wave shapes

Figure 9 and Figure 10 show the wave shape of the weak system source associated with the grid following inverters. Since the Grid following inverter requires interconnection to the main grid, it is no surprise that there was no major difference in their Inrush wave shape with the shape from a conventional synchronous generator.

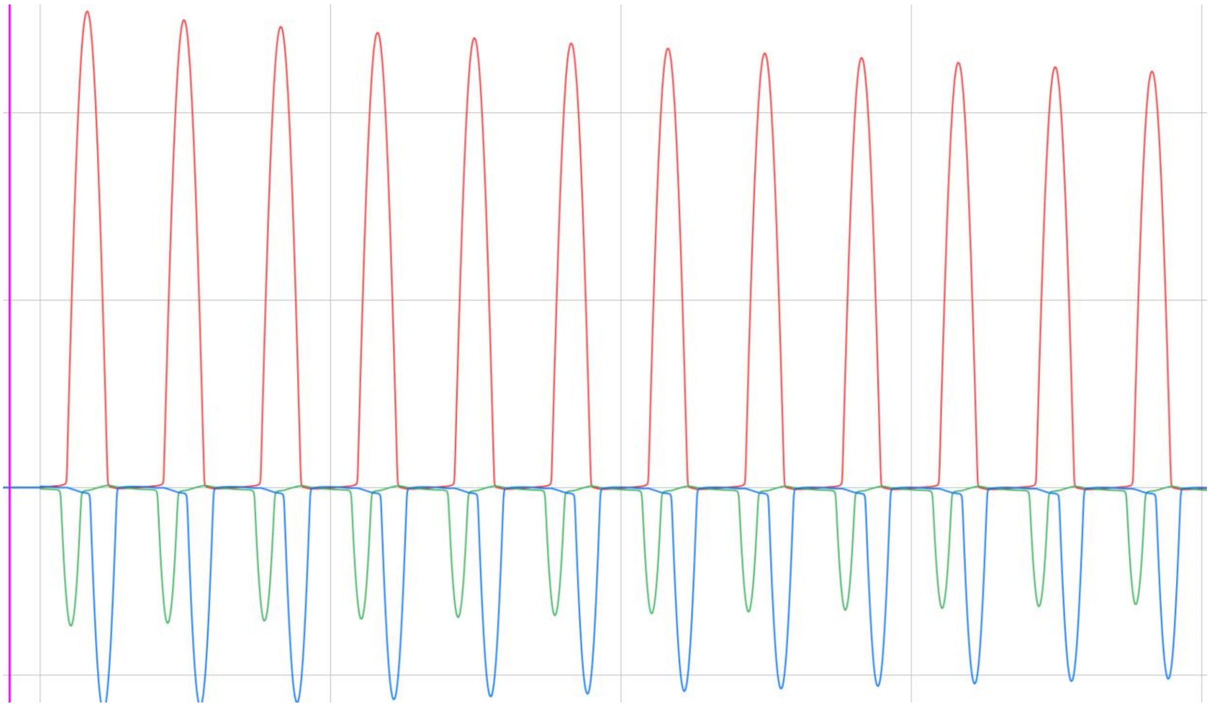


Figure 9. Grid Following #1 (500 MW)

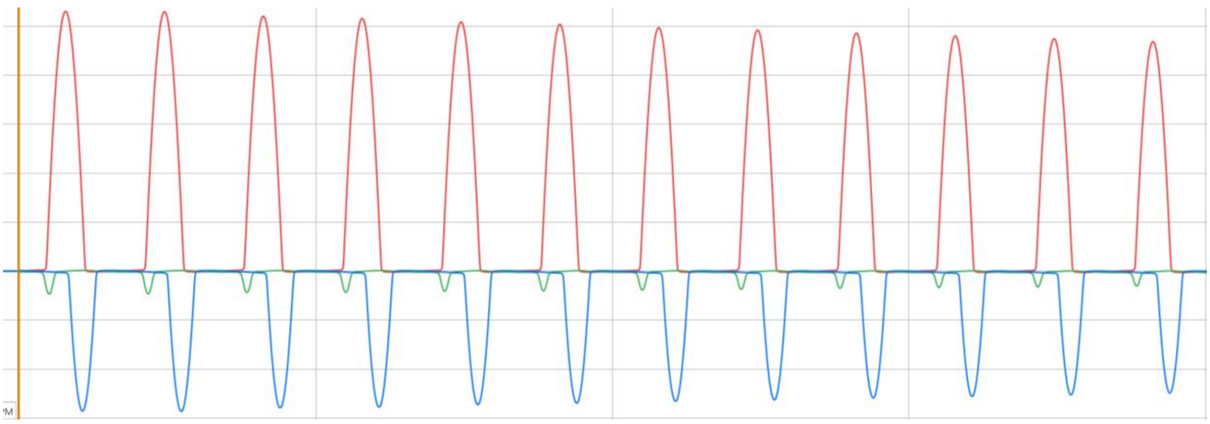


Figure 10. Grid Following #2 (1GW)

Figure 11 and Figure 13 show the shape of the decay of two grid-forming inverters. Grid forming inverter #1 shows an expected exponential type of decay that does not converge to 0A. The grid-forming inverter does not seem to be able to stabilize the inrush current.

Figure 12 and Figure 14 show the wave shape of the same two grid-forming inverters. It is striking how much difference the two inverter control designs present. The grid forming inverter #1 displays a current that appears similar to a typical waveshape but with sharp changes indicative of a greater harmonic content. Grid forming inverter #2 has smoother changes but the inrush size decreases sharply over the first 4 cycles before increasing again over the following 10 cycles.

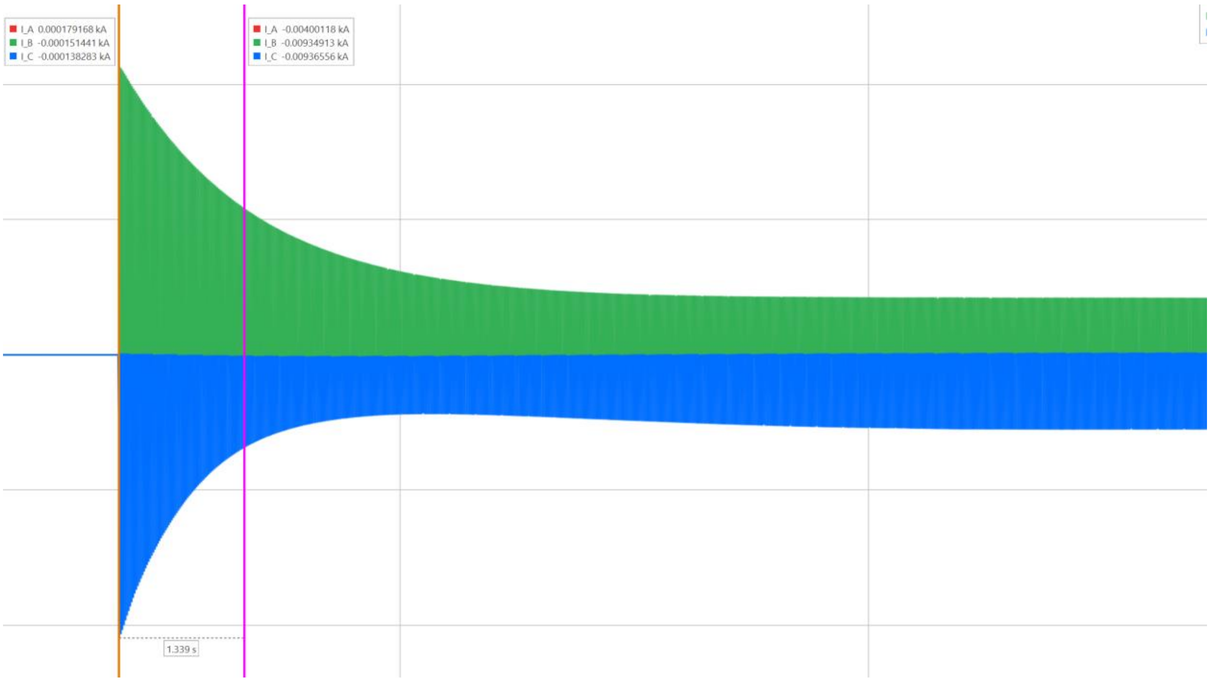


Figure 11. Grid Forming #1 (100 MW) extended view over 4s

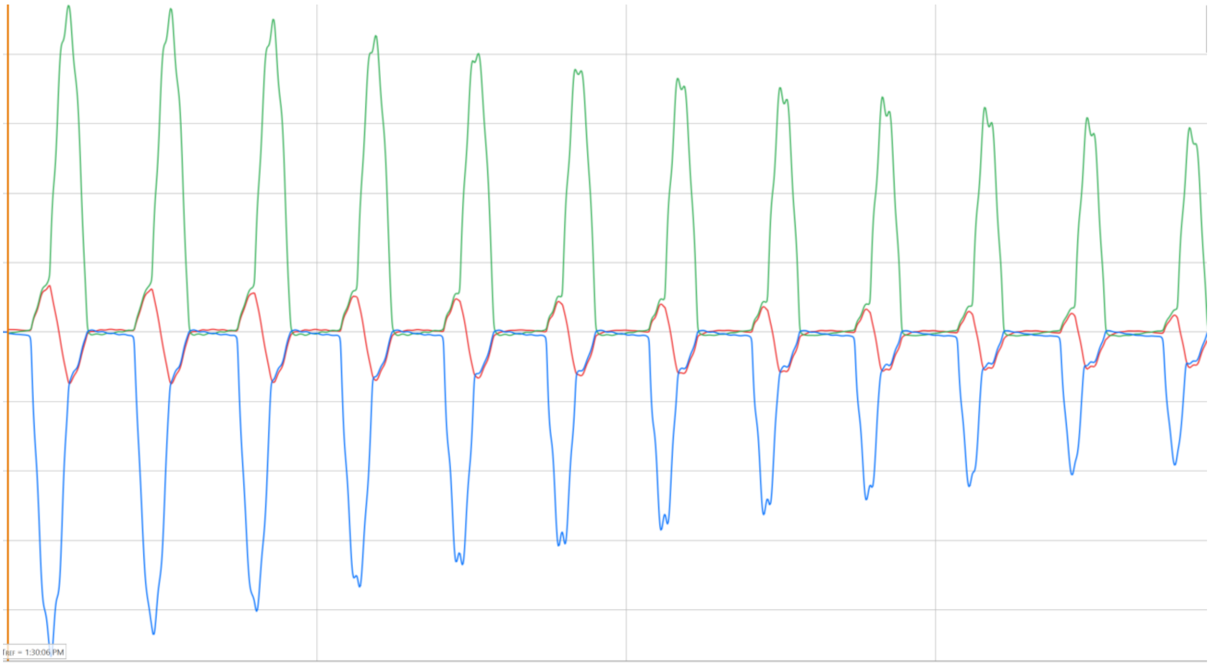


Figure 12. Grid Forming #1 (100 MW) first 12 cycles view

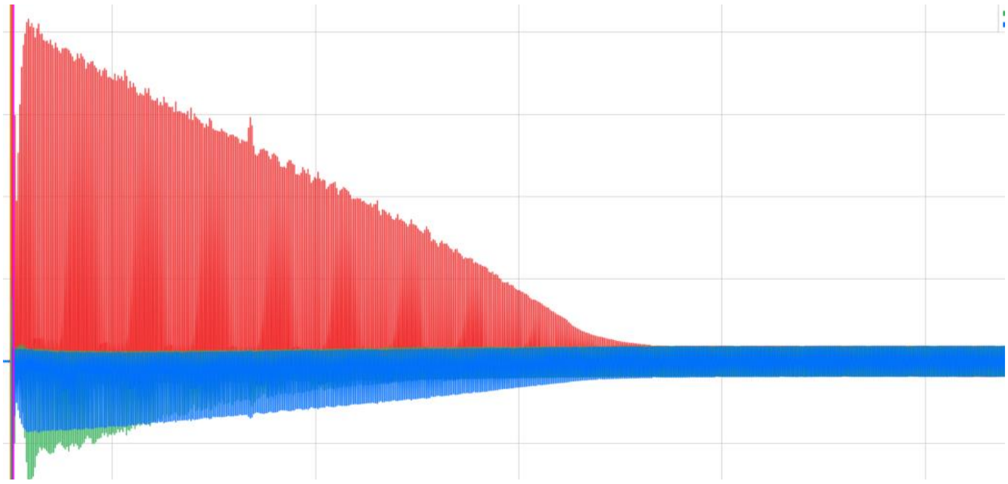


Figure 13. Grid Forming #2 (100 MW) extended over 4 seconds

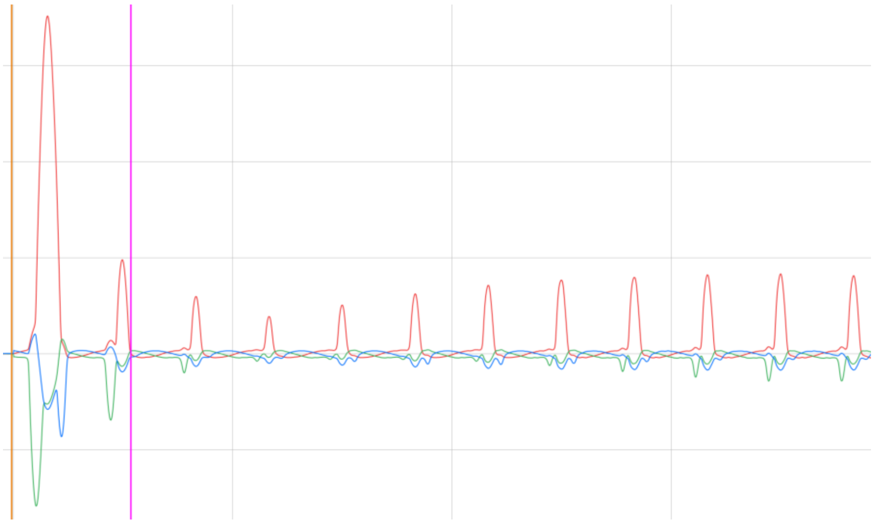


Figure 14. Grid Forming #2 (100 MW) first 12 cycles view

B. Peak current

It is notable that the grid following inverters are faring well with a minor reduction in peak current. The grid following #1 and #2 peaks stayed relatively constant with the size of the IBR supporting the inrush with small variations that do not appear to correlate with the size of the IBR. This may be an indication that a weaker system reference may be needed to find the limits in the controls. This contrasts with the Grid forming #1 which directly correlated with the size of the IBR. The Grid forming #2 is providing an output almost constant but slight inversely proportional, which is unexpected.

C. Voltage drop

The grid following #1 was not as successful in maintaining the voltage high during the transformer energization. The grid-following 2 was set with a capacitive VAR target to help maintain the pre-energization voltage. For this reason, it supported the voltage much better during the energization.

The Grid forming inverters have droop controls to respond to voltage and frequency changes, so they naturally responded to the in-rush voltage drop. Expectedly, the smaller the power rating, the larger the drop was.

These simulations show that energizing a larger transformer with a large penetration of Inverter-based resources can be challenging and should be studied carefully. This is especially true for grids sourced exclusively with inverters where grid forming inverters regulate the voltage and frequency.

D. Harmonic content

Protection relays often rely on harmonic content to identify Inrush. When the harmonic content is above a threshold, they may block the trip. Some relays may restrain by raising the tripping characteristic proportional to the harmonic content. 2^{nd} and 4^{th} harmonic are usually used to detect the magnetizing Inrush. 5^{th} Harmonic is used to mitigate overexcitation conditions on the transformer. Therefore, it is important to evaluate the Inrush harmonic content of the event generated. For this, we will take a close look at the content during the first 3 cycles of the Inrush.

In table 4, we present the harmonic contents found from the 2^{nd} to the 5^{th} harmonic. For each harmonic, we noted the percent harmonic content the lowest of each phase as well as the highest. For the 2^{nd} and 3^{rd} harmonic, we see little difference between the synchronous grid and the grid following inverters. For them, there is a slightly wider range of 4^{th} to 5^{th} harmonic % contents. Grid forming inverters present a wider range of harmonic content across all 4 studied harmonics.

Table 4 Harmonic Content Results

Main source	Source Impedance, MVA rating P, Q	2^{nd}	3^{rd}	4^{th}	5^{th}
Synchronous sources	0.1, 100, 0	55-81	12-57	7-31	6-11
Synchronous sources	1, 100, 0	54-75	12-51	7-31	6-11
Synchronous sources	10, 100, 0	54-80	12-56	7-31	6-11
Grid Following 1	NA, 100, 0	53-74	11-51	7-31	6-11
Grid Following 1	NA, 500, 0	55-82	14-63	7-45	7-25
Grid Following 1	NA, 1000, 0	57-85	16-74	5-61	1-47
Grid Following 2	NA, 100, -20	54-75	11-52	7-33	6-12
Grid Following 2	NA, 500, -25	55-83	16-54	6-45	2-25
Grid Following 2	NA, 1000, -30	56-88	15-75	7-61	7-45
Grid Forming 1	NA, 100, 0	46-110	6-66	3-49	3-47
Grid Forming 1	NA, 500, 0	11-89	3-77	8-64	6-51
Grid Forming 1	NA, 1000, 0	22-77	4-49	1-25	1-7
Grid Forming 2	NA, 100, 0	41-75	17-53	23-36	20-35
Grid Forming 2	NA, 500, 0	66-84	54-73	36-62	18-50
Grid Forming 2	NA, 1000, 0	75-87	46-75	21-62	4-50

Grid forming Inverter #1, present a standing Inrush-like with a peak of 34% of the unit rating after the Inrush decay. As presented in Figure 14, this waveform contains more than 80% of 2nd harmonic content on phase B and C (64% of 3rd, 48% of 4th, 25% of 5th).

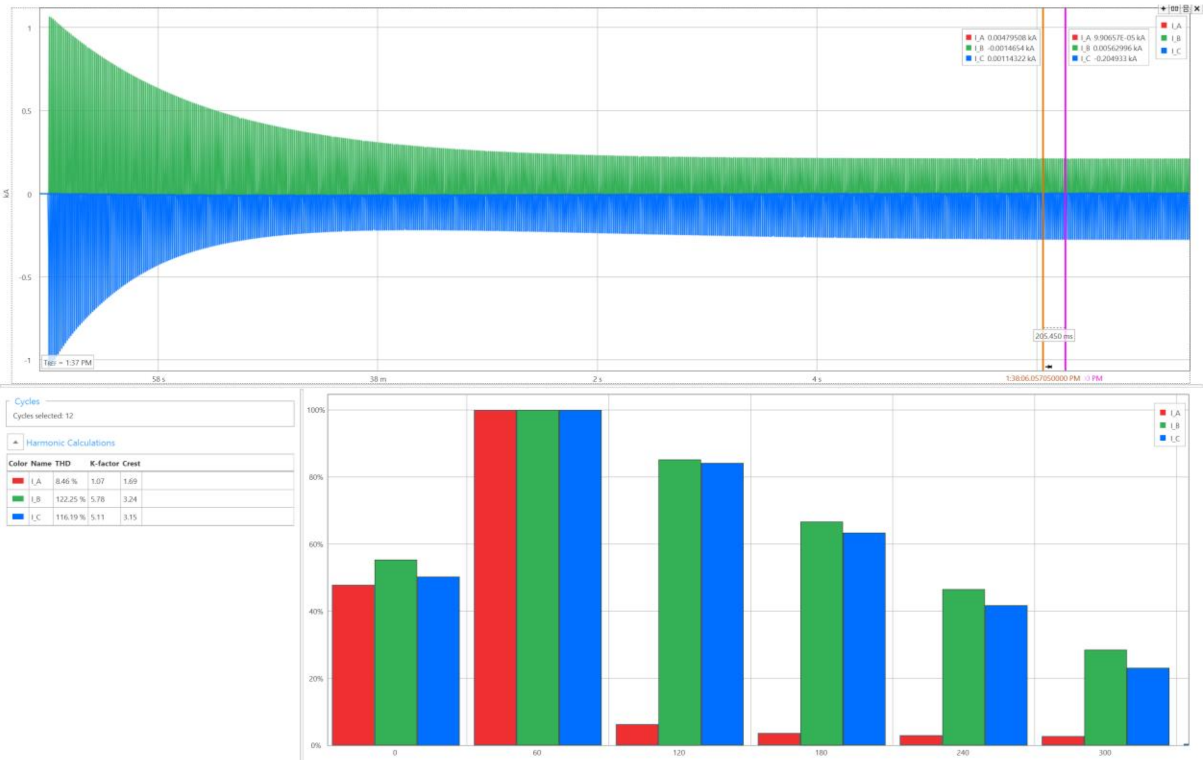


Figure 14. Grid Forming #1 (1000 MW) Harmonic content after the decay

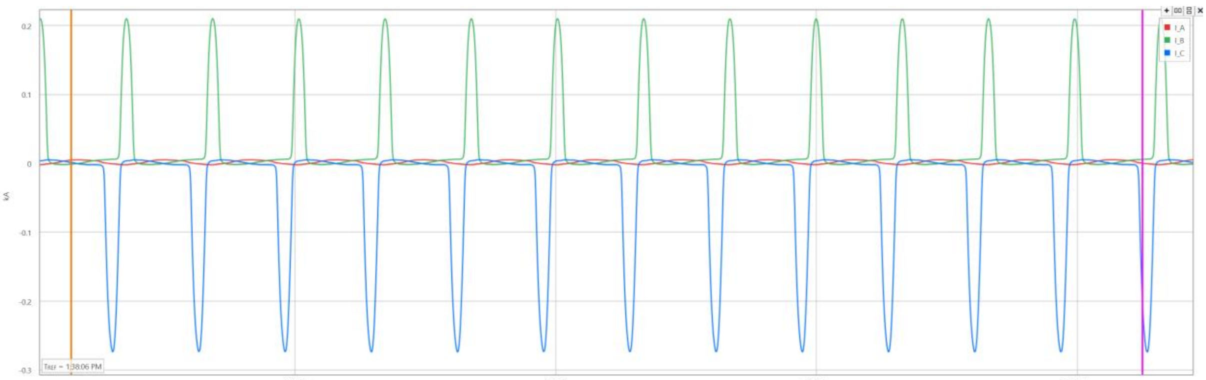


Figure 15. Grid Forming #1 (1000 MW) wave form detail after the decay

E. Influence of the inverter

The Grid following inverter can help strengthen the power supply in weak grid conditions and can fare well in supporting transformer inrush.

Grid forming inverter-based transformer energization showed very different behaviors and inrush that did not decay fully. This is an indication that careful control EMTP studies are necessary when implementing grid forming inverters. The constant inrush content may be limiting the transformer's ability to carry load.

Table 4 presents a summary of the results of the peak currents and voltage drops. There is no obvious difference in the waveform of the Inrush currents:

Table 4 Summary of the Results

Main source	Source Impedance, MVA rating P, Q	Peak Amps	Time to 50%	Time to 10%	Voltage drop	Time below 0.95 pu
Synchronous sources	0.1, 100, 0	1,375	1.052	2.702	0.9987	NA
Synchronous sources	1, 100, 0	1,360	1.057	2.691	0.9903	NA
Synchronous sources	10, 100, 0	1,226	1.083	2.718	0.9164	1.418
Grid Following 1	NA, 100, 0	1,243	1.067	2.720	0.9685	NA
Grid Following 1	NA, 500, 0	1,271	1.042	2.650	0.9727	NA
Grid Following 1	NA, 1000, 0	1,217	0.996	2.501	0.9763	NA
Grid Following 2	NA, 100, -20	1,223	0.057	2.671	0.9678	NA
Grid Following 2	NA, 500, -25	1,182	0.998	2.485	0.9728	NA
Grid Following 2	NA, 1000, -30	1,254	1.079	2.681	0.9778	NA
Grid Forming 1	NA, 100, 0	470	0.266	1.389	0.8623	0.259
Grid Forming 1	NA, 500, 0	993	0.745	Unstable	0.9660	NA
Grid Forming 1	NA, 1000, 0	1,063	1.384	Unstable	0.9756	NA
Grid Forming 2	NA, 100, 0	1,212	1.060	2.660	0.8503	0.027
Grid Forming 2	NA, 500, 0	1,181	1.015	2.483	0.9384	0.025
Grid Forming 2	NA, 1000, 0	1,161	0.821	2.151	0.9672	NA

Protection relay challenges

The results from the harmonic contents are very clear. There will be very challenging situations in securing the differential protection relays for transformer Inrush. While all inverters studied provided sufficient 2nd harmonic content to restrain or block under Inrush conditions, we found a wider range of content with grid forming inverters. More problematic is the possible high persistent 2nd harmonic content that could reduce the ability to trip or slow down the trip decision for fault inside the transformer.

Similarly, the 5th harmonic blocking for overexcitation conditions could also interfere with the trip when used. The persistent Inrush content encountered with the grid forming #1 will appear as a constant differential quantity that will need to be accounted for when setting the relays.

Based on the level of voltages and currents seen in the simulated events, there is no obvious apparent challenges to distance and over-current relays.

CONCLUSION

Energizing a transformer with inverter resources can present some challenges as proportionally larger local inverter resources may be required to avoid larger voltage drop during energization.

There are strong indications that the harmonic contents, sometimes persistent presented by IBR sourced transformer will create relay settings determination difficulties. It is advisable that system engineers study these conditions whenever the penetration of inverters is high.

In follow-up research, we plan on using the COMTRADE signal generated by the PSCAD simulation to test the security of the relays during the energization events. We will also generate a range of internal fault scenarios to find if the sensitivity and trip speed may have been compromised by the secured relays.