Investigation into Vulnerability of Synchronous Machines to Large Load Subsynchronous Active Power Variation

ERCOT LLWG Meeting Oct 24, 2025

ELECTRANIX
SPECIALISTS IN POWER SYSTEM STUDIES

Background

- AI training processes can exhibit fast variation in active power.
- Key concern: active power variation impact on synchronous machines.
- Electranix contracted by ERCOT to:
    - Demonstrate synchronous machine impact by large load due to active power variations (2025).
    - Support the development of potential approaches and requirements (e.g., requirement and criteria)
    - Expect to publish the final report by Q1 2026
- Then ERCOT plans to work with the industry to develop requirements as needed to mitigate the risk.
- First stage is to communicate learnings and solicit feedback. Today!!

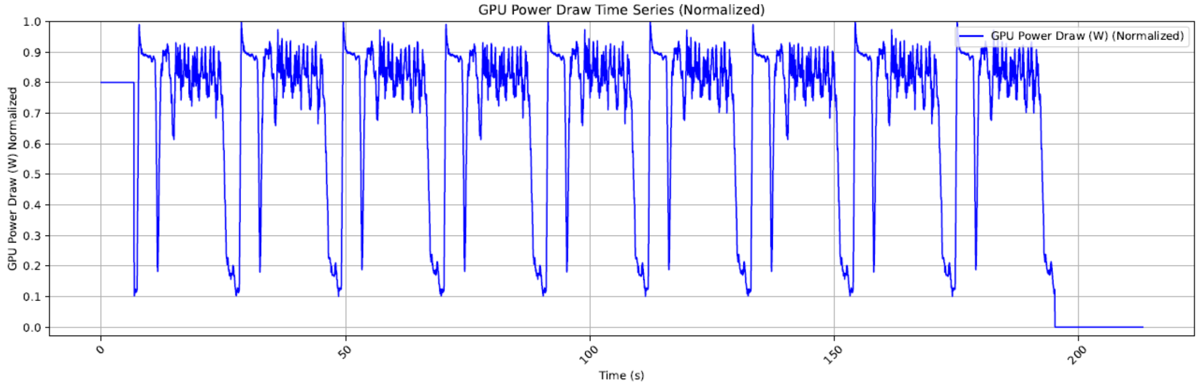


Fig. 1. Power readings from an at-scale training job on DGX-H100 racks.

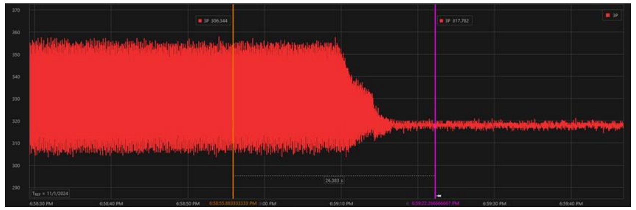
Power Stabilization for AI Training Datacenters

Esha Choukse, Brijesh Warrier, Scot Heath, Luz Belmont, April Zhao, Hassan Ali Khan, Brian Harry[1], Matthew Kappel, Russell J. Hewett[1], Kushal Datta, Yu Pei, Caroline Lichtenberger, John Siegler, David Lukofsky[1], Zaid Kahn[1], Gurpreet Sahota, Andy Sullivan, Charles Frederick, Hien Thai, Rebecca Naughton[1], Daniel Jurnove, Justin Harp[1], Reid Carper, Nithish Mahalingam, Srini Varkala, Alok Gautam Kumbhare, Satyajit Desai, Venkatesh Ramamurthy, Praneeth Gottumukkala, Girish Bhatia, Kelsey Wildstone, Laurentiu Olariu, Ileana Incorvaia, Alex Wetmore, Prabhat Ram, Melur Raghuraman
Mohammed Ayna, Mike Kendrick, Ricardo Bianchini
Microsoft

Aaron Hurst, Reza Zamani, Xin Li, Michael Petrov, Gene Oden, Rory Carmichael
OpenAI

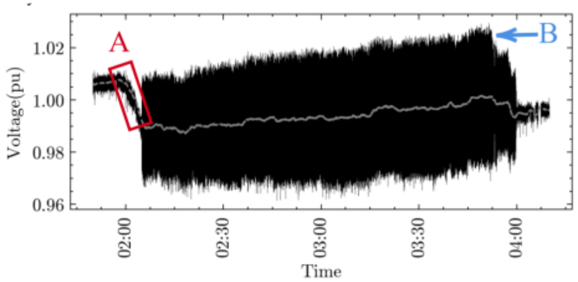
Tom Li, Apoorv Gupta, Pratikkumar Patel, Nilesh Dattani, Lawrence Marwong, Rob Nertney, Hirofumi Kobayashi, Jeff Liott, Miro Enev, Divya Ramakrishnan, Ian Buck, Jonah Alben
NVIDIA

Has this occurred in the field? Yes (July 2025 LLWG Recap)



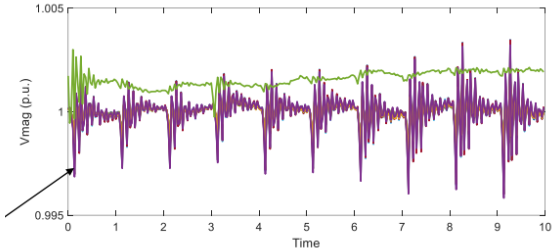
- ERCOT 23 Hz Event (July-October 2024)

https://www.ercot.com/files/docs/2025/02/28/LL-Oscillation_LFLTF_Mar2025_Final.pptx



- Dominion Energy 14.7-14.8 Hz Event

https://www.researchgate.net/publication/389098360_Understanding_the_Inception_of_147_Hz_Oscillations_Emerging_from_a_Data_Center



- Dominion Energy 1-11 Hz Event

https://www.epri.com/events/539b60d7-57da-4252-9968-fb1754ee3b66

- SSO can cause catastrophic damage or fatigue to generator equipment

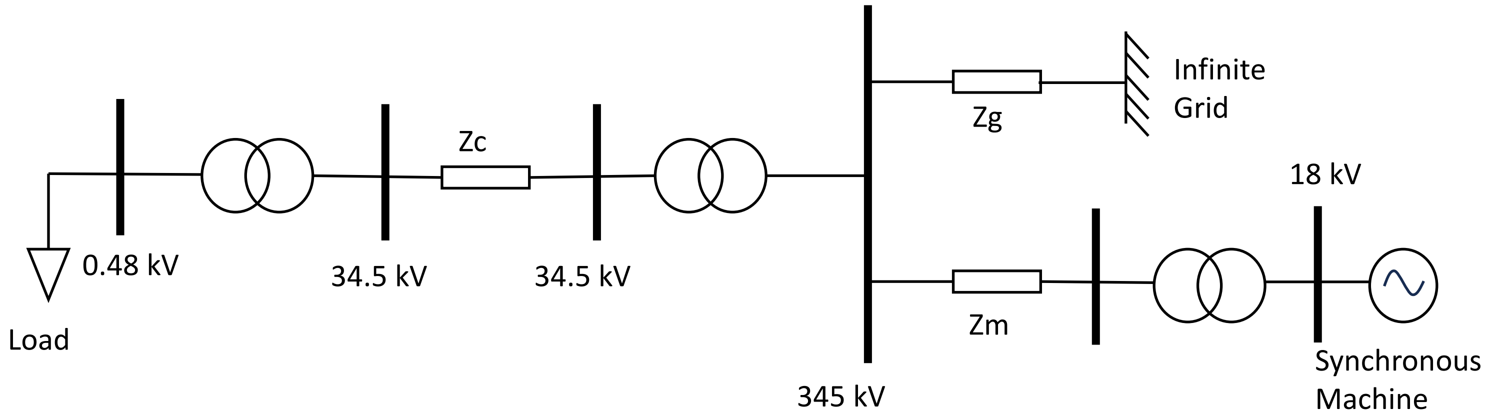
Example: synchronous generators (1970 Mohave event)

Project Team

- Electranix:
  - Kasun Samarawickrama, Technical Manager
  - Lukas Unruh, General Manager
  - Andrew Isaacs, Vice President

- ERCOT:
  - Supported by teams from System Planning and Operations

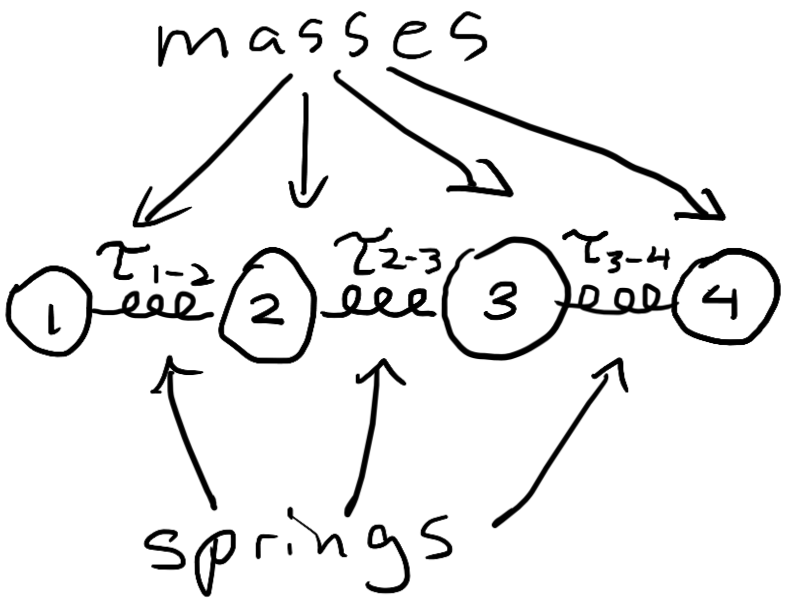
Impact Demonstration

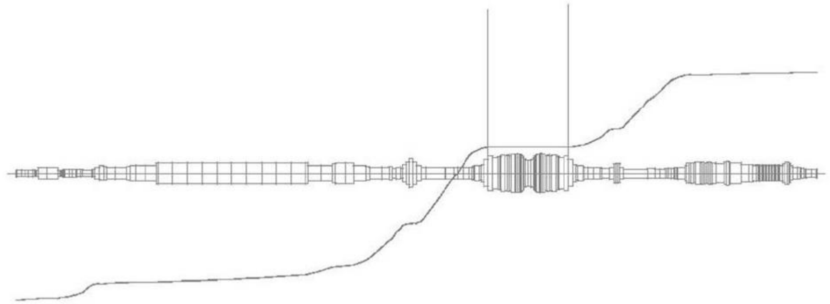


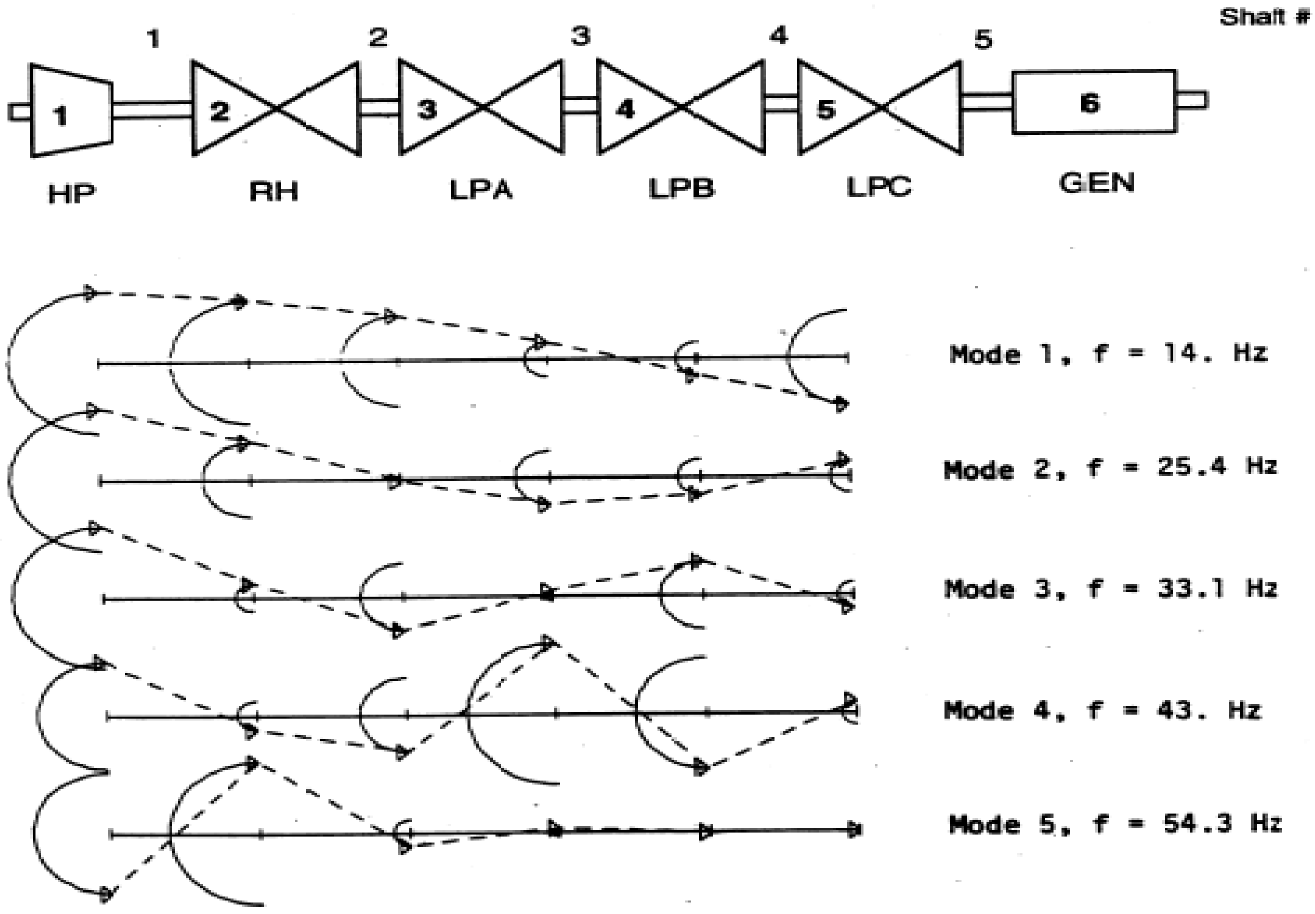
Key Parameters:

- Machine Rating = 100 MW
- **Synchronous machine key torsional mode: 12 Hz**
- Load profiles:
  - 1 - Fixed frequency square wave varying between 25 MW and 100 MW with a ramp rate of 10 MW/1ms
  - 2 - Proxy waveform mimicking measured AI training load profile

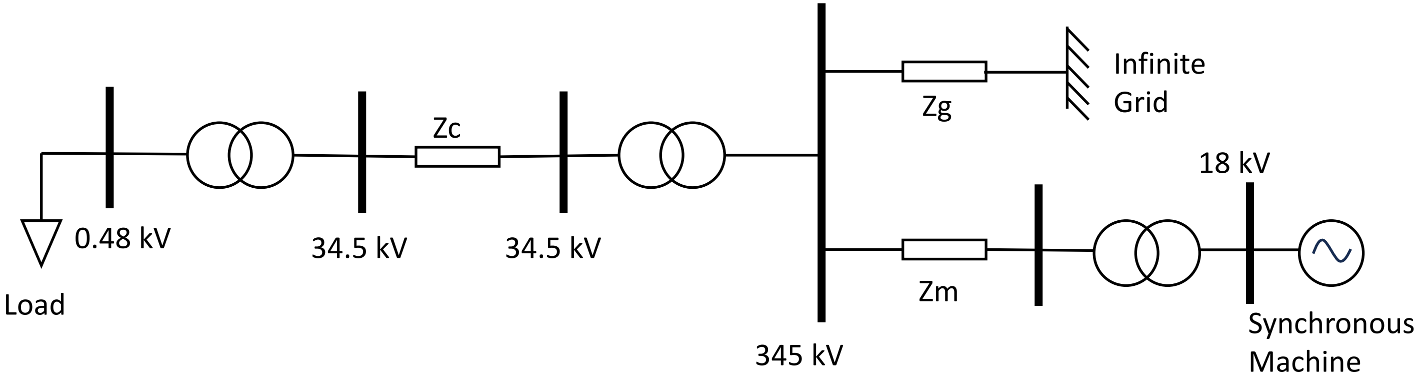
Reminder… Synchronous Generator Shaft







Summary of Results



Key Parameters:

- Machine Rating = 100 MW
- **Synchronous machine key torsional mode: 12 Hz**
- Load profiles:
  - Profile 1 (S1 – S8): Fixed frequency square wave varying between 25 MW and 100 MW with a ramp rate of 10 MW/1ms
  - Profile 2 (S9 – S16): Proxy waveform mimicking measured AI training load profile

Scenario No.	Load Variation	Max Pk-Pk Active Power Variation* (Generator electrically close: Zm = 0)			Alternating Torque	
		At the Load	At the Machine	At the Grid	Tau12 (pu)	Tau23 (pu)
	Hz	MW	MW	MW		
S1	Load profile 1 at 2 Hz	76.81	32.98	77.81	0.233	0.234
S5	Load profile 1 at 12 Hz	77.61	11.89	82.55	5.124	5.028
S9	Load profile 2	85.55	6.21	87.44	0.042	0.042
S13	Load profile 2 with 12 Hz oscillations	88.86	8.09	92.22	0.993	0.974

**Note: Split of active power between machine and grid is initially determined by impedance split, and the final variation will depend on the frequency of the variation and other machine characteristics over time.*

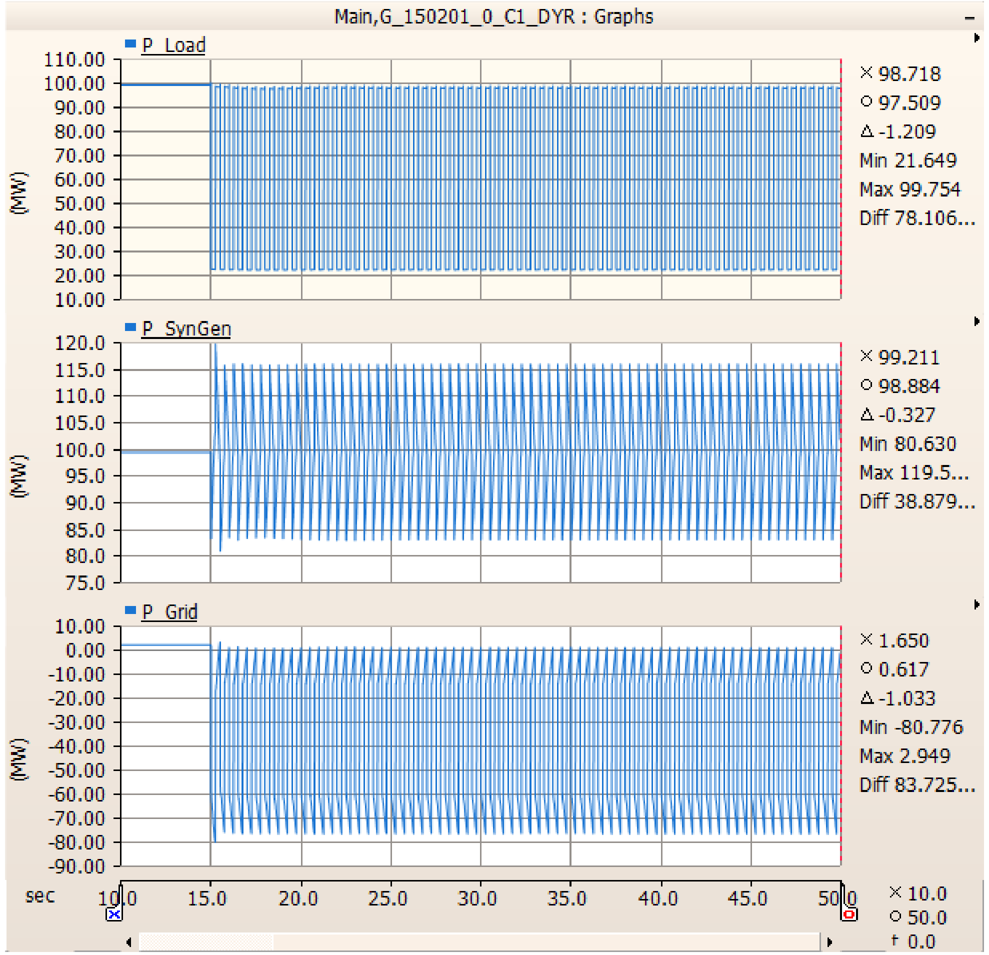
Load profile 1 (Square wave) at 2 Hz – Scenario S1

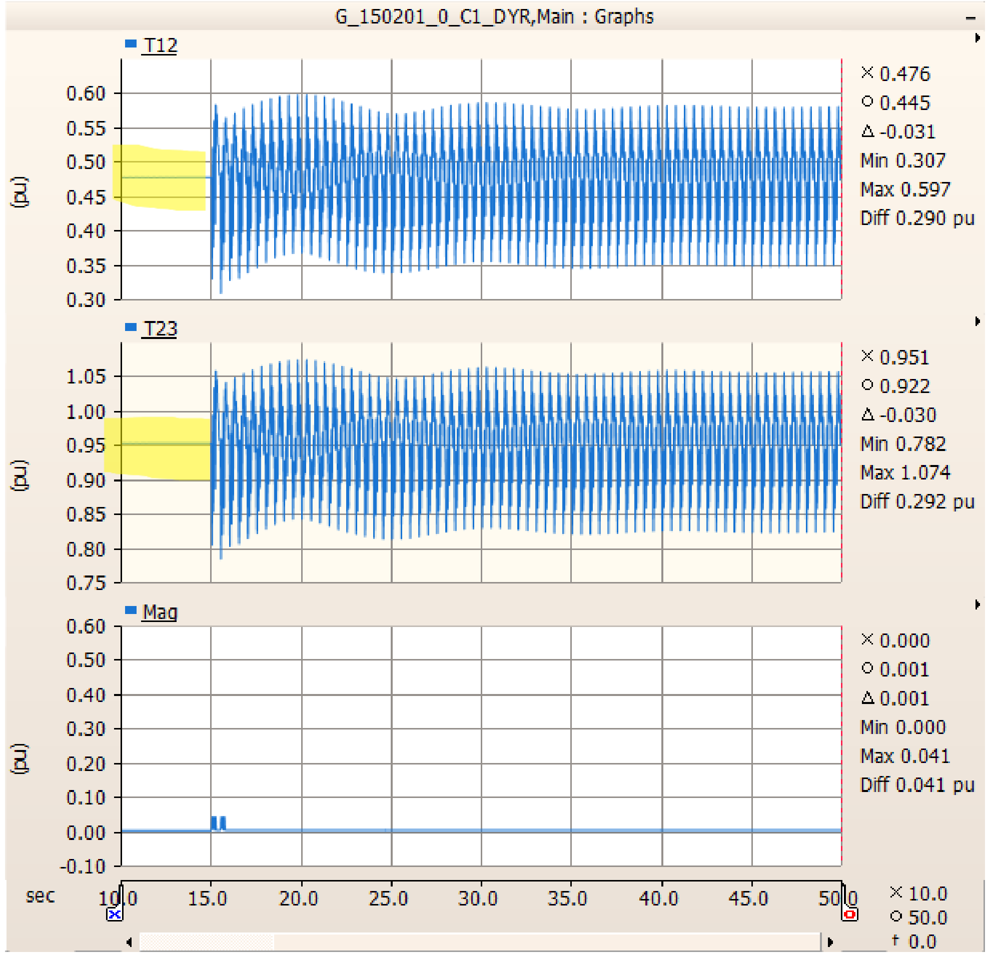
>0.2 pu torque! (acceptable to the machine design?)

P Load

P Gen

P Grid





Torque 12

Torque 23

Per unit 12 Hz Component

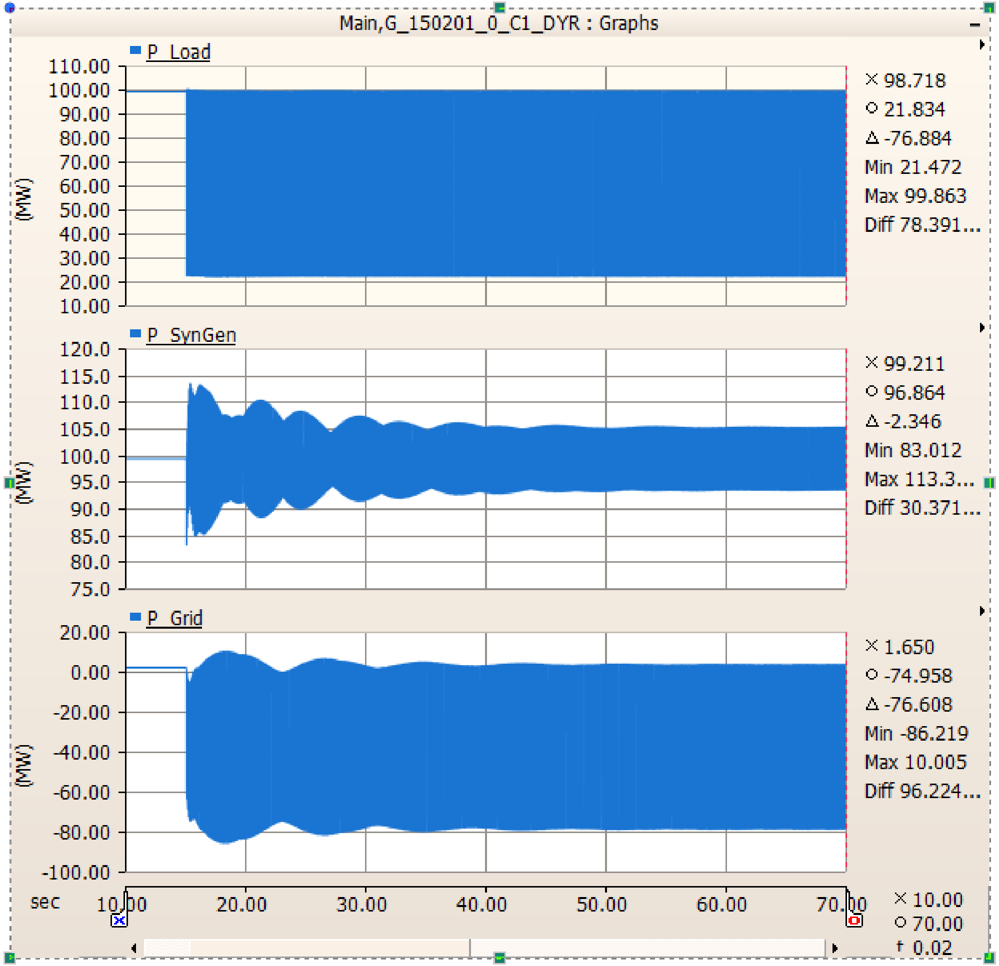
Load profile 1 (Square wave) at 12 Hz – Scenario S5

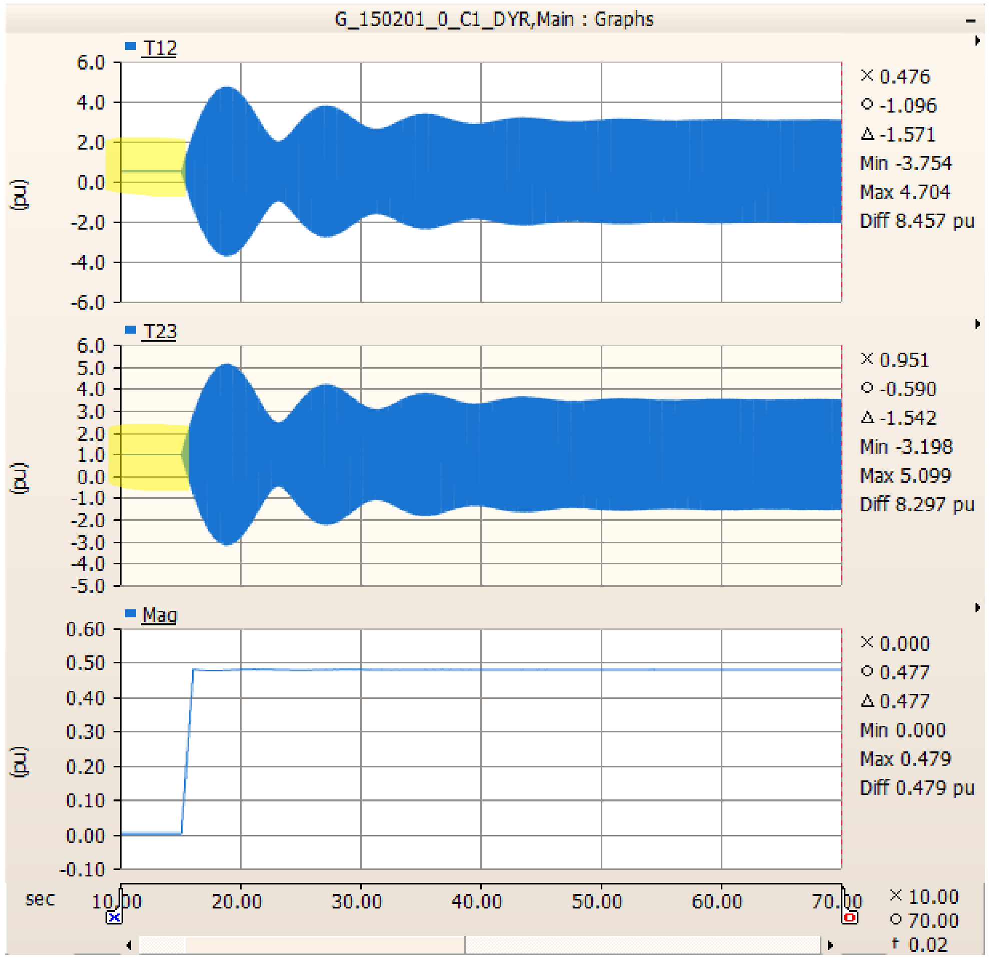
>5 pu torque! (acceptable to the machine design?)

P Load

P Gen

P Grid





Torque 12

Torque 23

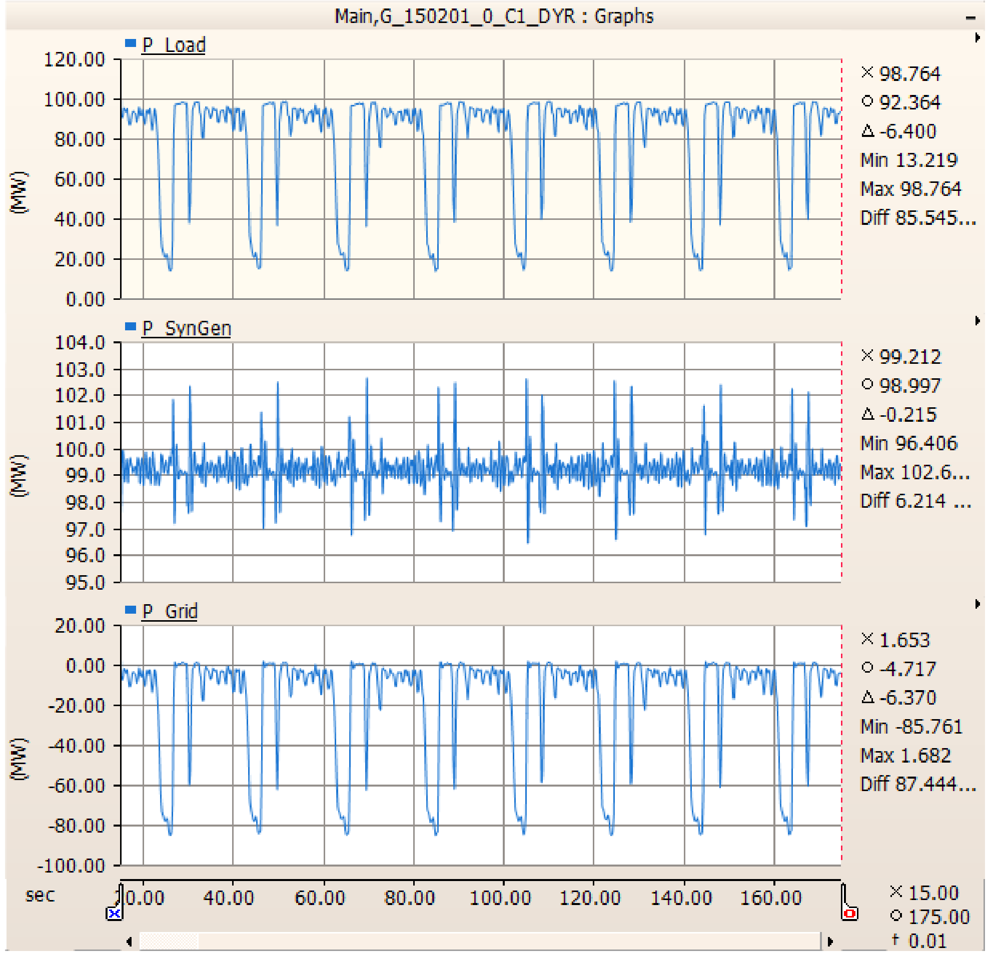
Per unit 12 Hz Component

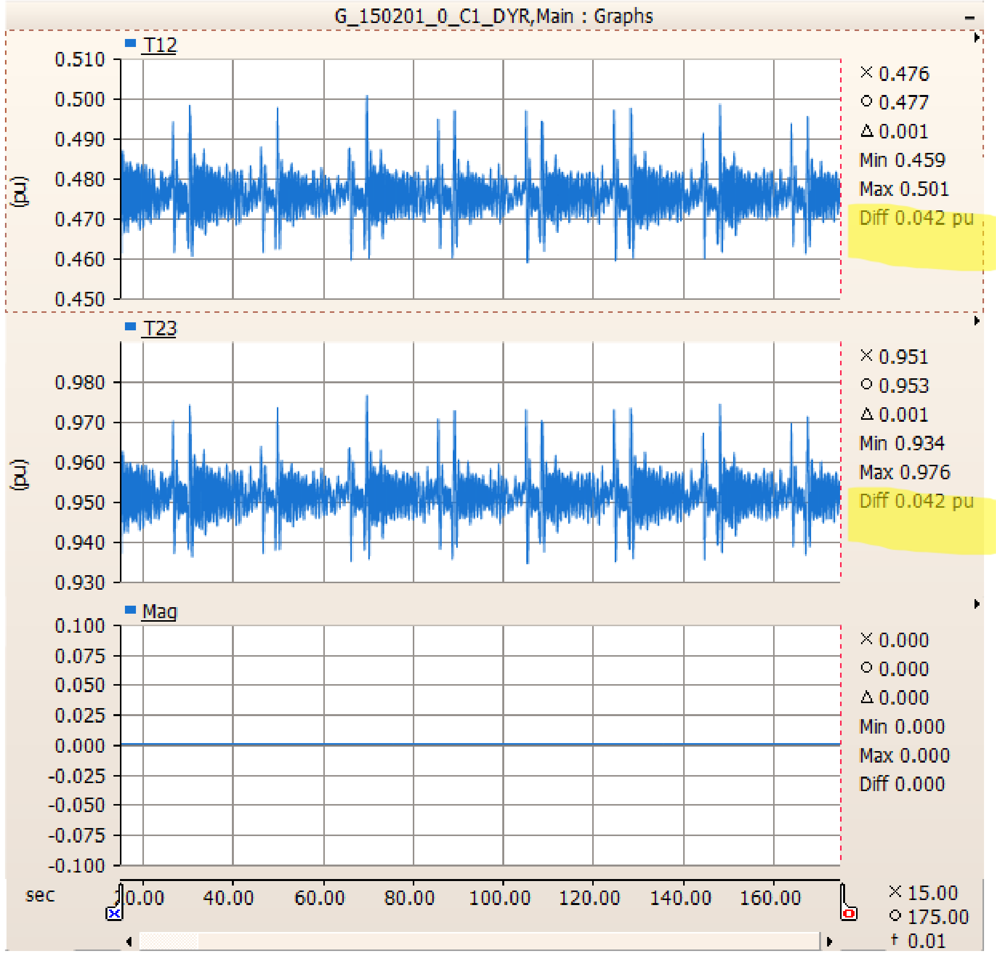
Load profile 2 – Scenario S9 (similar to paper on slide 2)
4% Torque (acceptable to the machine design?)

P Load

P Gen

P Grid





Torque 12

Torque 23

Per unit 12 Hz Component

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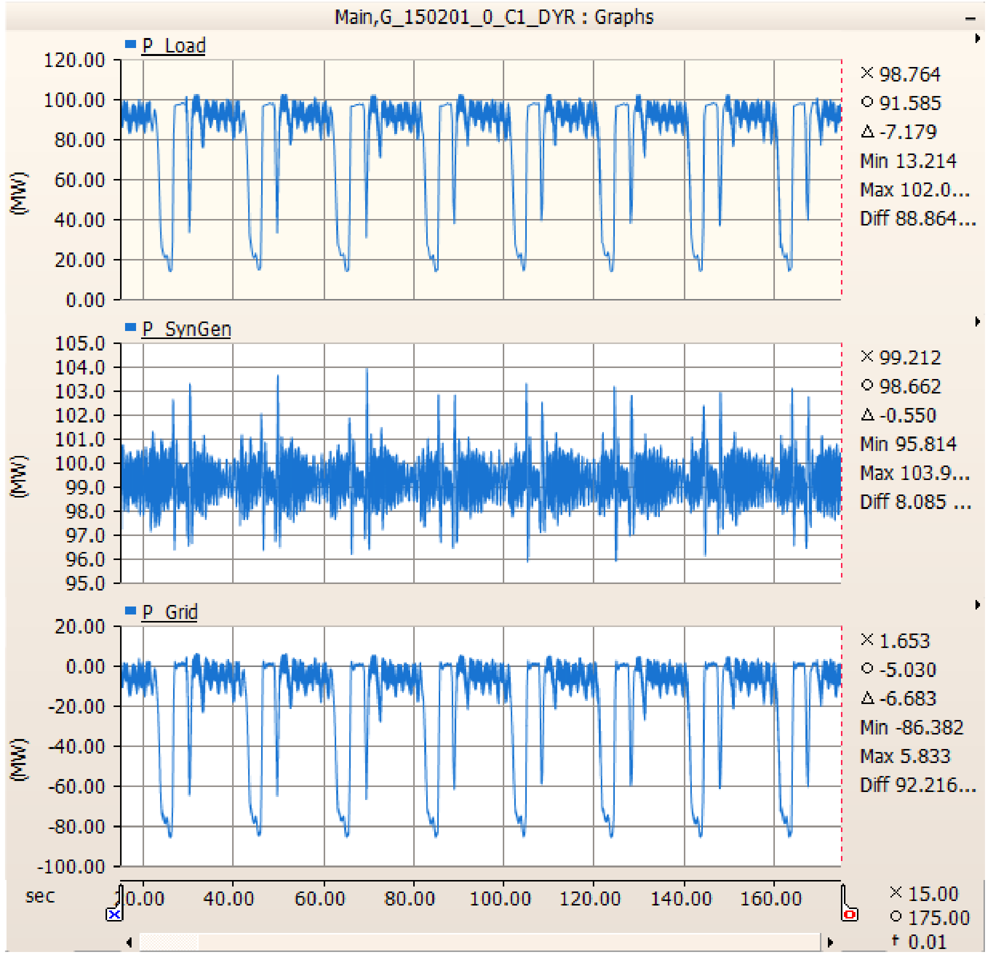
Load profile 2 with 12 Hz – Scenario S13 (similar to paper on slide 2) **(acceptable to the machine design?)**

1pu Torque… strong Torque Amplification!

P Load

P Gen

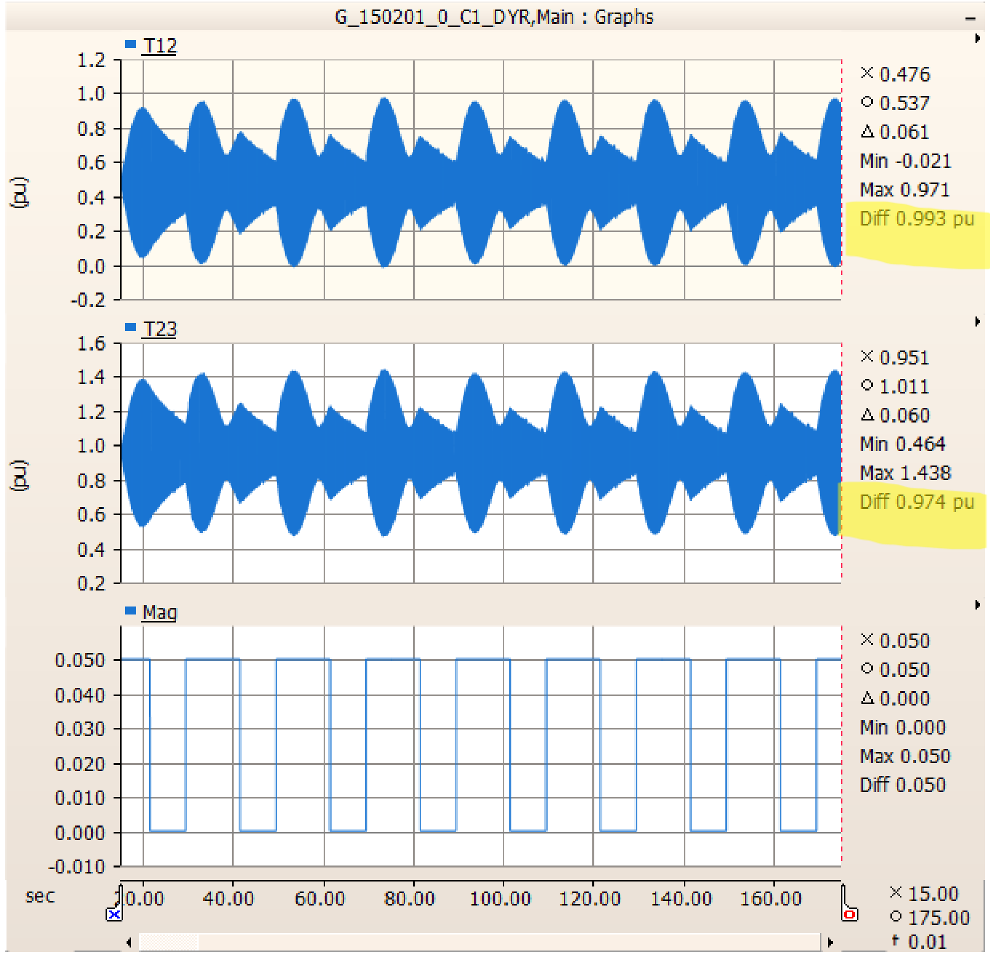
P Grid



Torque 12

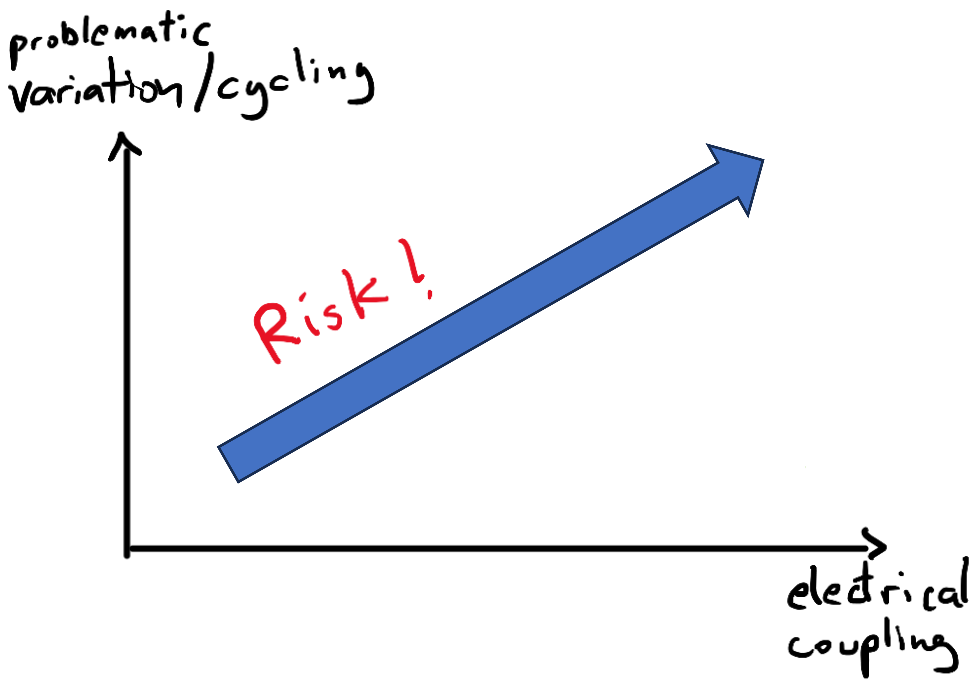
Torque 23

Per unit 12 Hz Component



Key takeaways from simulations

- Risk to synchronous generators depends first and foremost on load characteristics (cycling, ramping, subsynchronous characteristics), and secondly on network topology between load and generators
  - AI training load profiles can result in persistent torque perturbations on synchronous generator shafts
- Loads with load cycling and co-located load/generator facilities are at high risk
- If loads are far away and don’t contain problem frequencies, then we see less than 4% torque, less than 10% active power at terminals.
- If we assume worst case load behaviours, then we see >>100% torque (low impedance to generator, torsional component present), >30% active power at terminals!!



More information is required!

- Additional details are needed to help manage the risk and requirement development. For example:
  1. Other than shaft torque and electrical proximity, are there other considerations which go into determining acceptable limits for continuous active power variation at generator terminals? For example, equipment vibration, governor activation, field currents, or other? Consider that the active power variation may be repetitive or quasi-periodic, and may persist for many years.
  2. Are there levels of active power variation that are acceptable regardless of frequency content? For example, 2% of machine rating? 10%?
  3. When considering cyclic shaft torque (assuming machine operating at full power) do you have guidance for endurance limits or high cycle fatigue? For example, 0.1 pu torque?

Some takeaways

- The potential for resonance between load and synchronous generators depends on their location and operational characteristics (such as active power variation)
- Generator owners should consider actively monitoring for potential resonance and consult with generator OEMs if any concerns arise
- It is essential for Loads to understand the potential impact on the grid and generators. Measures should be taken to mitigate software cycling via energy storage or hardware/software solutions. While perfect flatness is not required, active power must be sufficiently stable by the time it is introduced to the grid
- ERCOT is proactively addressing this issue by engaging consultants and monitoring industry practices to develop best practices and needed requirements to ensure grid security

American Transmission Company (ATC) load requirements (Effective Now)

- ATC (Transmission Service Provider under MISO footprint) has had a large influx of data center interconnection applications, and some of them are in advanced construction stages.
- ATC published requirements on ride-through, active power variation, power factor, etc.
- Reproduced here as an example of a load-based requirement. A similar requirement in ERCOT may be part of an overall solution.

- New load requirements are in two parts:
- Load Interconnection Guide, rev 15 – published August 22, 2025 (pages 32-35)
- ATC Planning Criteria, V25 – published August 28, 2025 (pages 34-37)

ATC	Criteria	Department:	System Planning
		Document No:	PLG-CR-0001-V25
Title: Transmission System Planning Criteria		Issue Date:	August 28, 2025
		Previous Date:	February 4, 2025

ATC

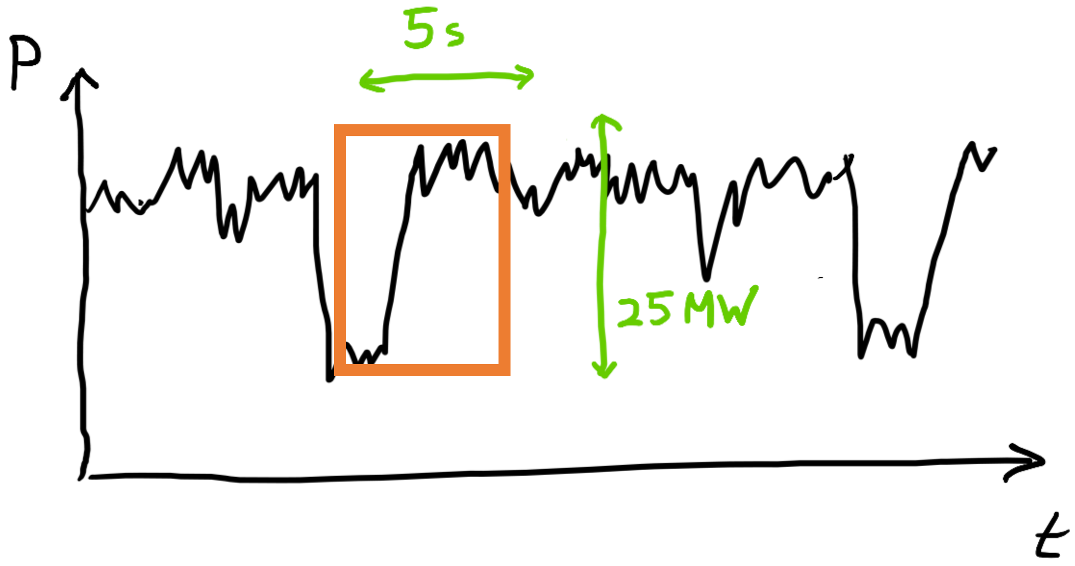
Load Interconnection Guide

Revision 15.0
August 22, 2025

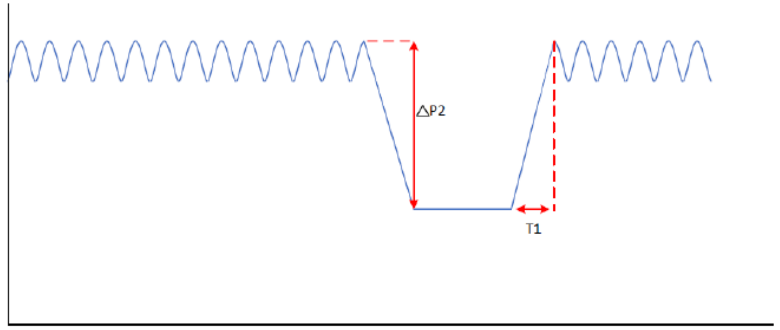
ATC Planning Criteria for Active Power Variation:

Table 9.1-1: Active Power Oscillation Criteria Limits

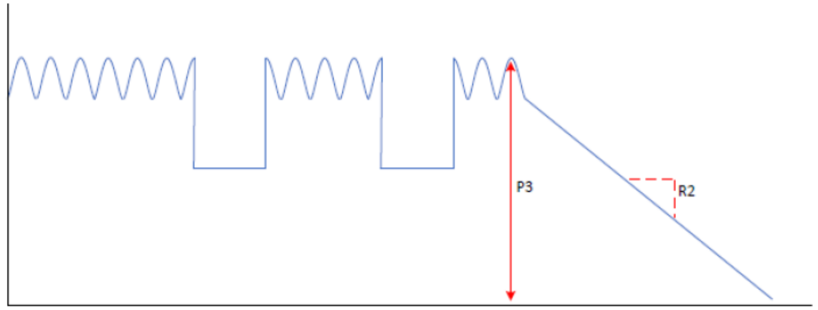
Constant	Limit	Unit
ΔP2	25	MW
T1	5	seconds
P3	50	MW
R2	0.5	MW/second (MW/s)



Criterion 1: Repetitive changes in load active power must be <ΔP2 for any period of time <T1 seconds calculated using a sliding time window.



Criterion 2: Any change (increase or decrease) in active power >P3 MW should be limited to <R2 MW/s.



Next Steps

- ERCOT intends to provide updates as necessary. The final report is anticipated to be completed in the first quarter of 2026.
- ERCOT invites stakeholders, OEMs, and industry experts to provide comments and suggestions on managing and mitigating this risk.
- For any questions or feedback regarding this topic, please direct your emails to the addresses provided below. Ensure all recipients are copied.
  - **Jonathan.Rose@ercot.com**;
  - **Jimmy.Zhang@ercot.com**;
  - **LargeLoadInterconnection@ercot.com**

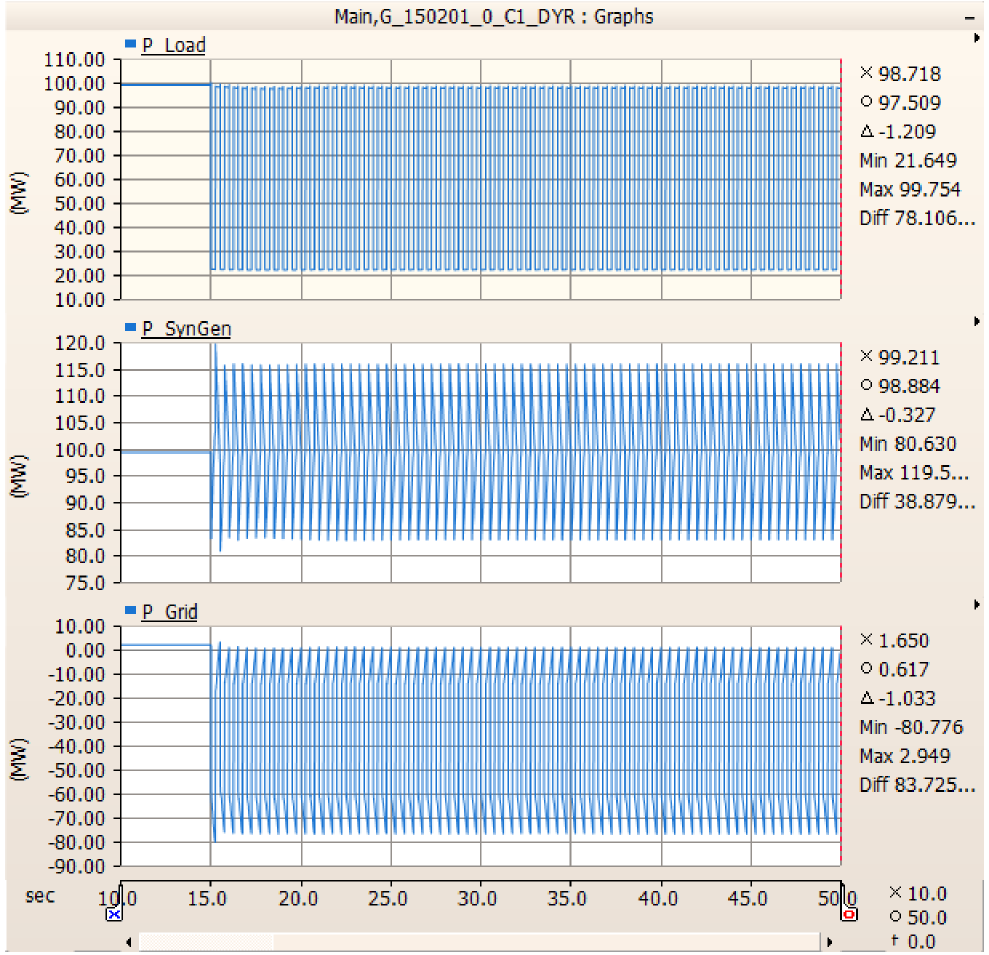
Additional Simulation results

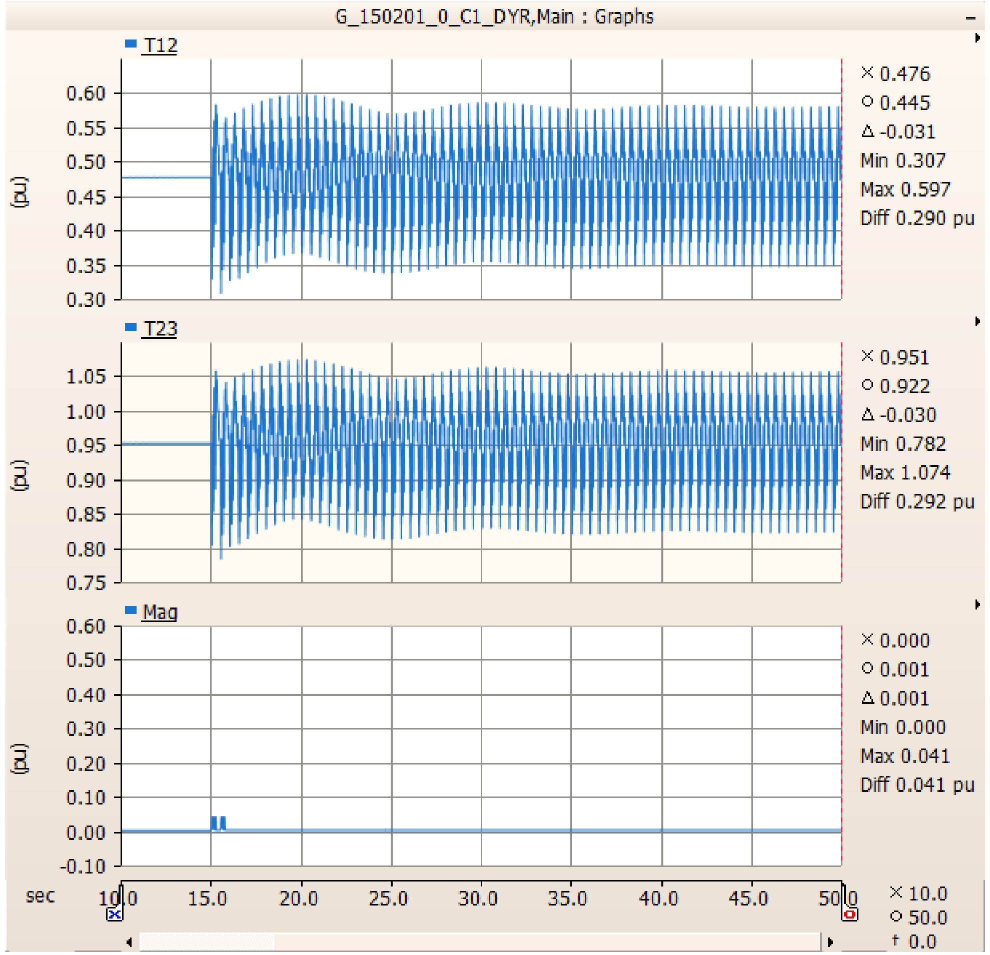
Results – Square Wave Load Profile

Scenario No.	Load Variation	Impedance		Active Power Variation			Alternating Torque	
		Grid (Zg)	GenTie (Zm)	At the Load (ΔPl)	At the Machine (ΔPm)	At the Grid (ΔPg)	Tau12 (pu)	Tau23 (pu)
	Hz	pu	pu	MW	MW	MW		
S1	2	0.100	0.000	76.81	32.98	77.81	0.233	0.234
S2	2	0.100	0.050	76.90	26.59	75.83	0.195	0.197
S3	2	0.100	0.100	76.95	21.73	74.69	0.165	0.166
S4	2	0.100	0.250	76.96	12.65	73.88	0.108	0.108
S5	12	0.100	0.000	77.61	11.89	82.55	5.124	5.028
S6	12	0.100	0.050	77.63	9.84	82.11	5.042	4.948
S7	12	0.100	0.100	77.62	8.44	81.86	4.953	4.860
S8	12	0.100	0.250	77.54	5.72	81.36	4.627	4.541

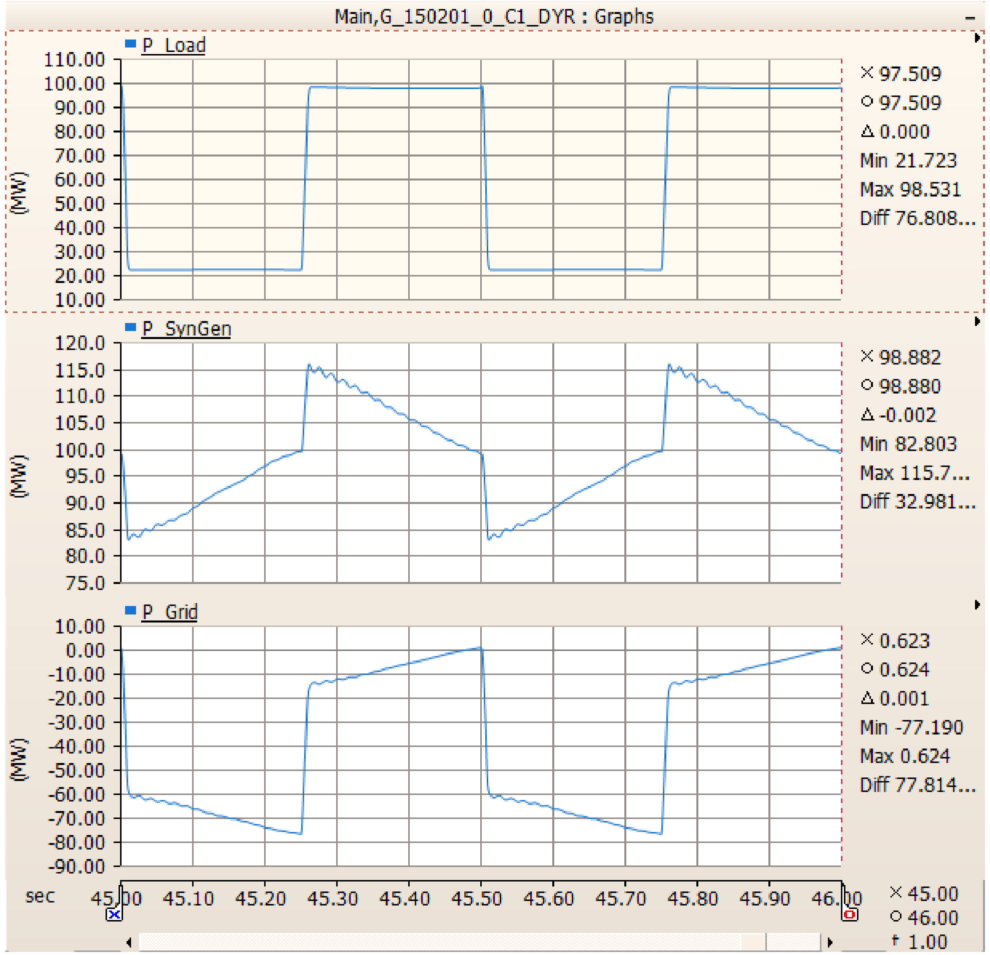
Note: All pu values are based on 100 MVA

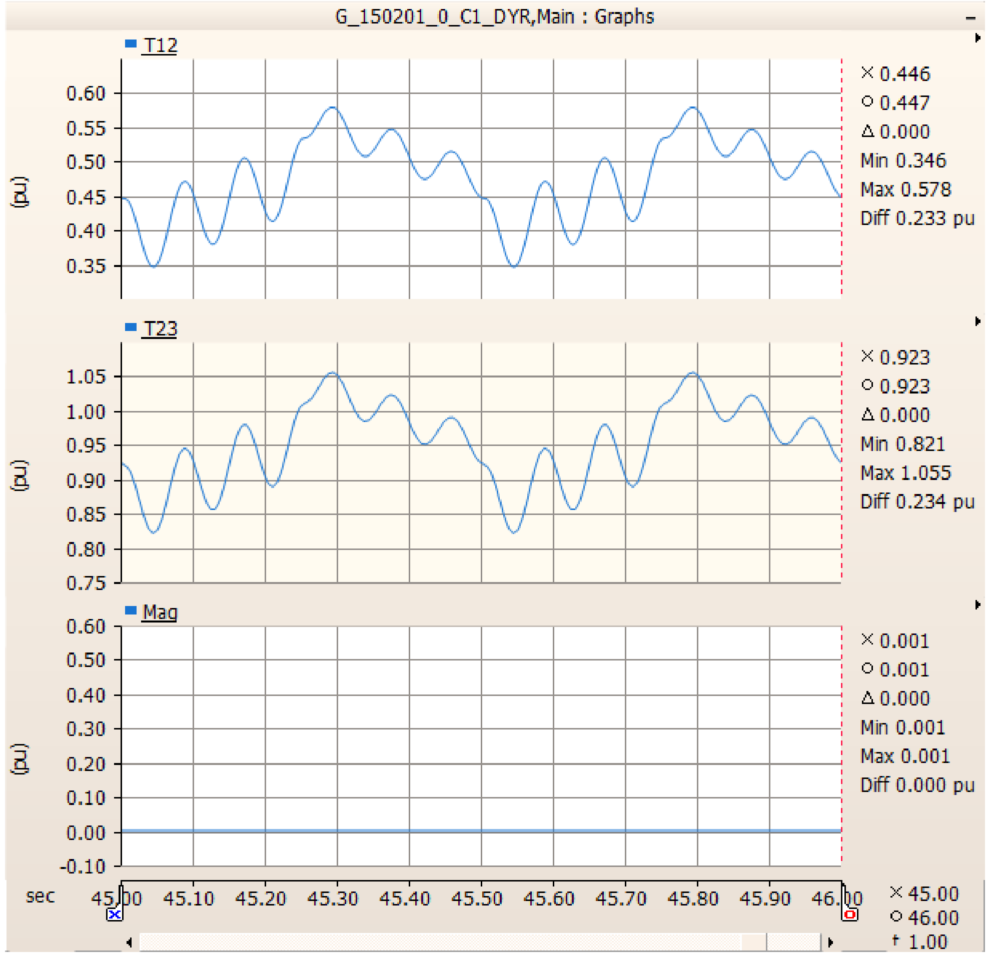
Sample Traces – S1



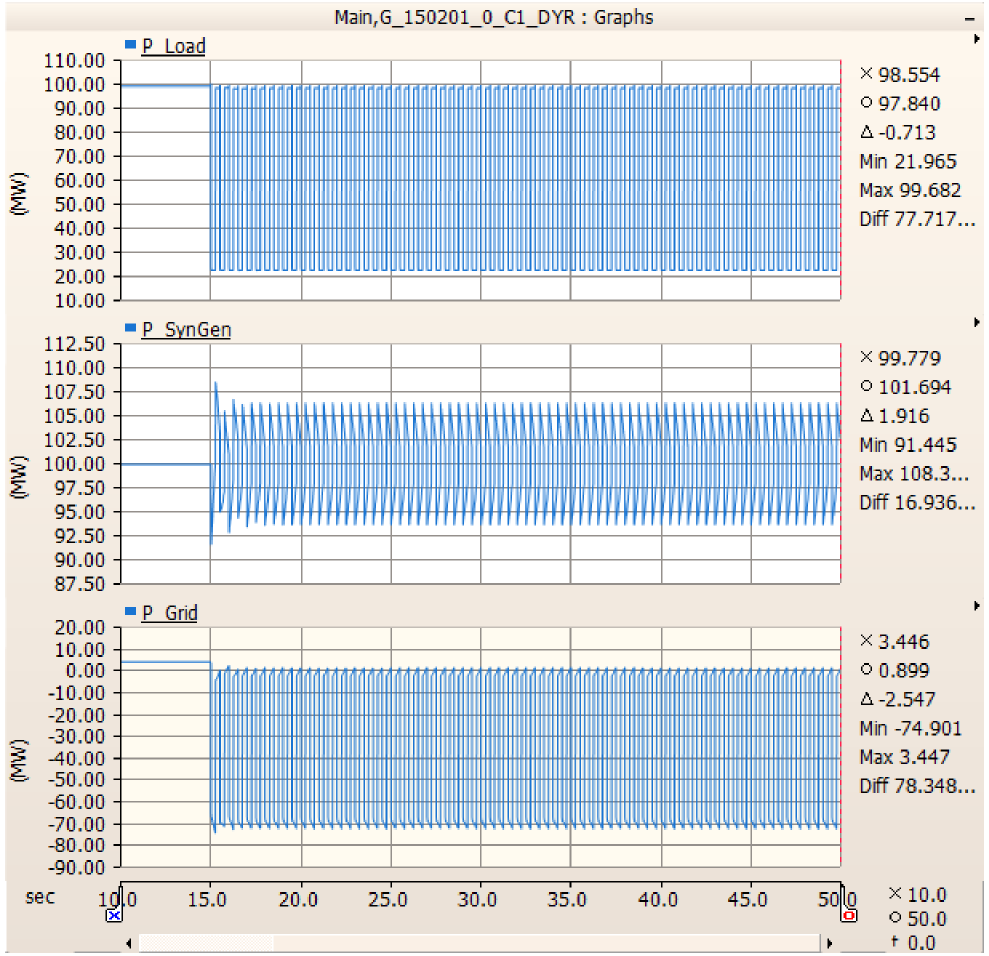


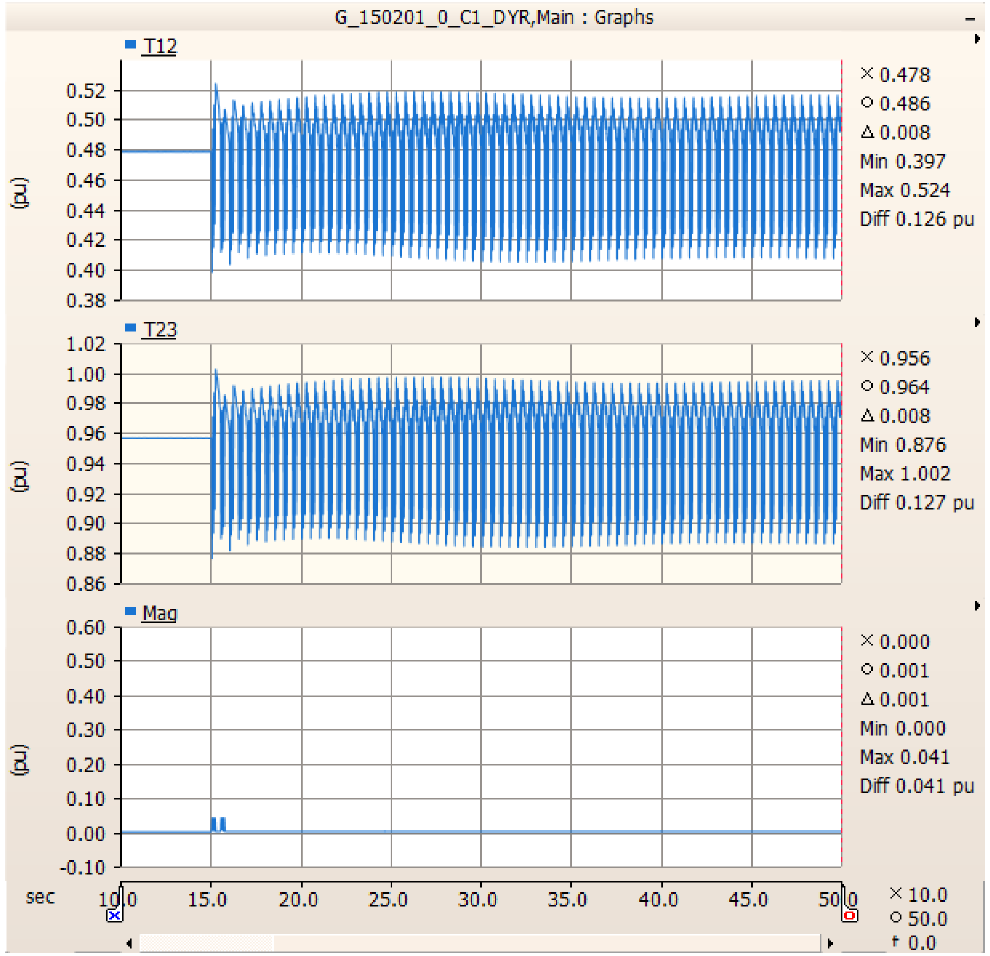
Sample Traces – S1 (Zoomed)



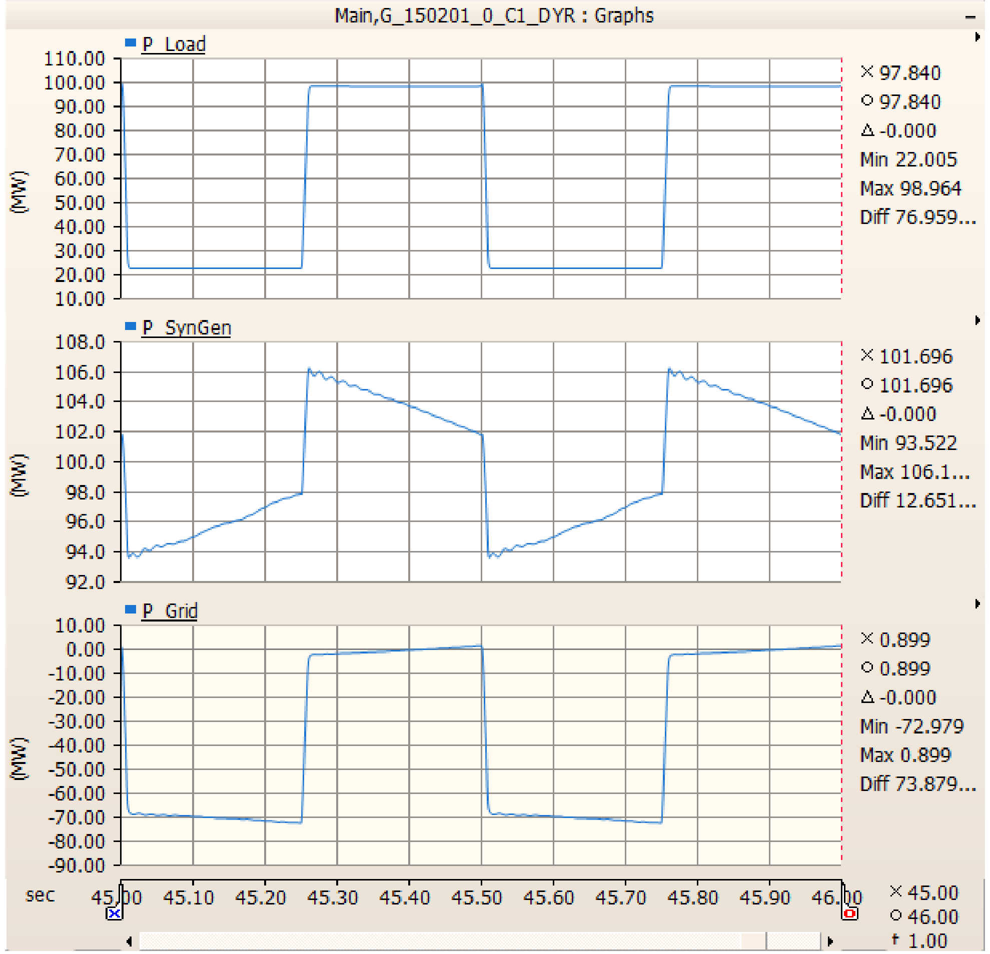


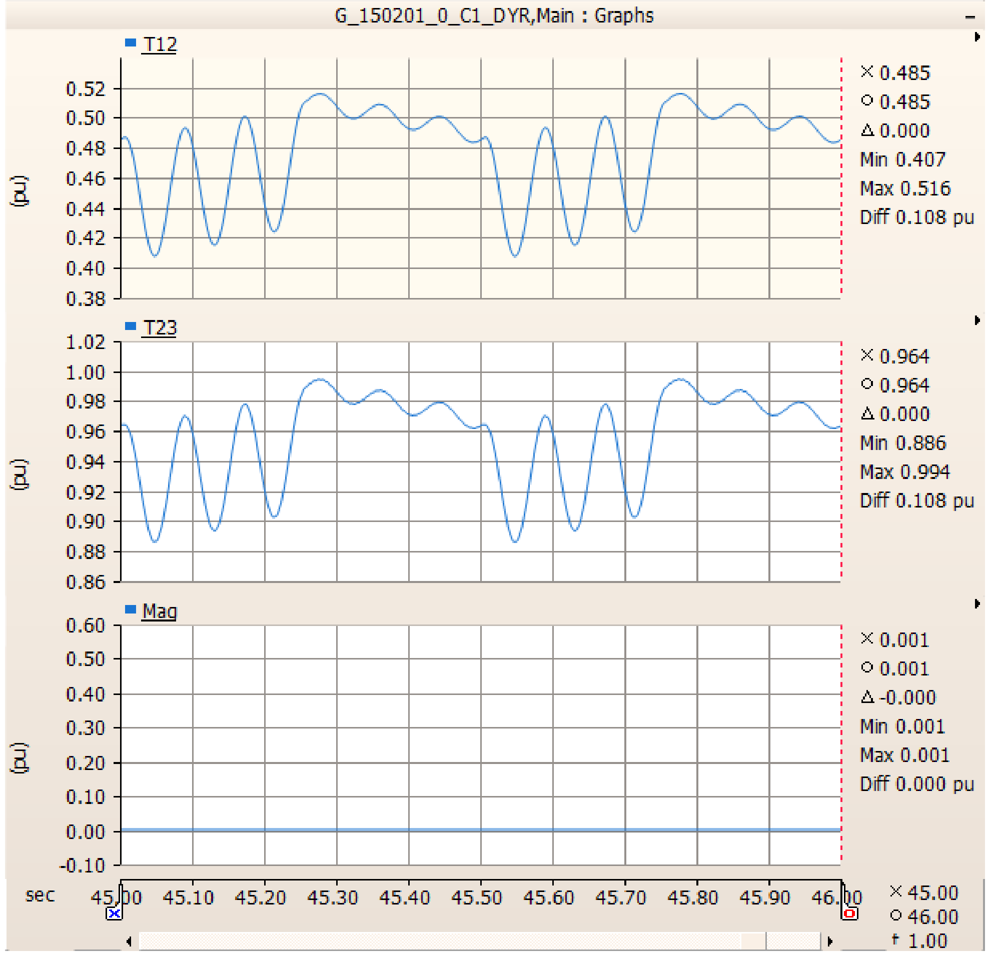
Sample Traces – S4



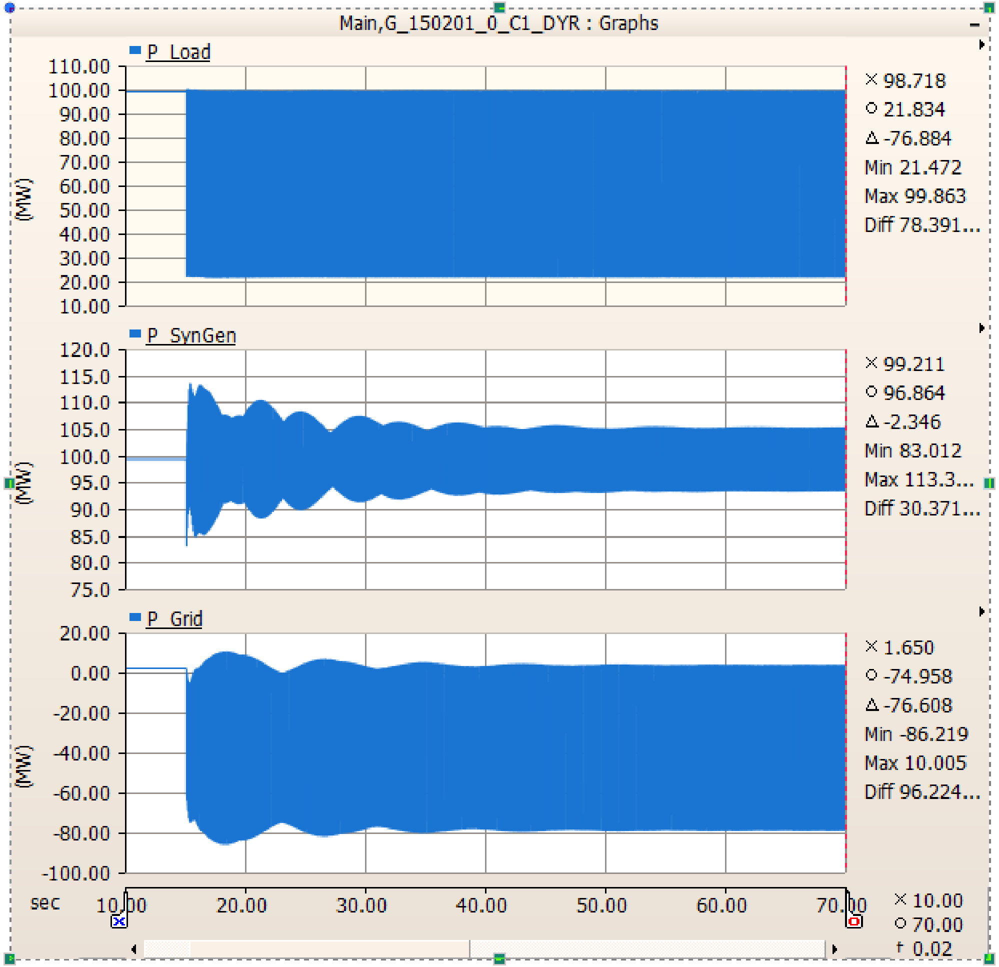


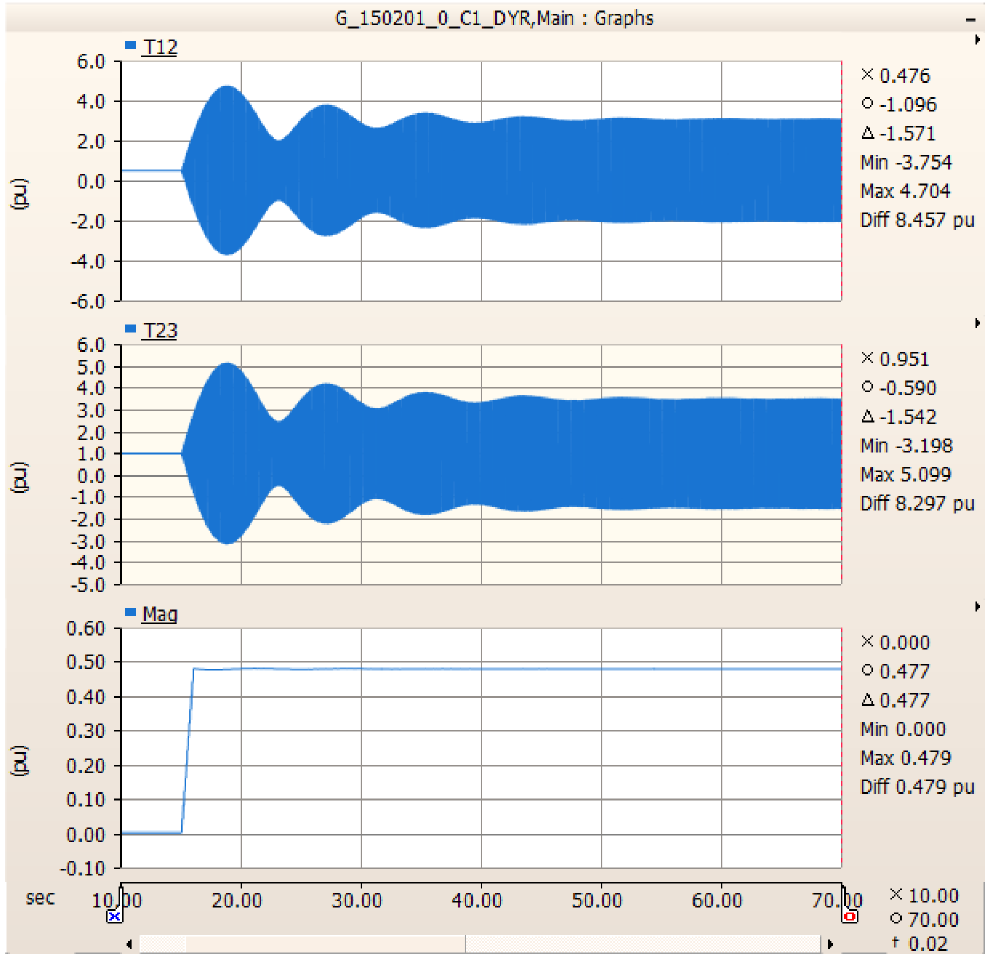
Sample Traces – S4 (Zoomed)



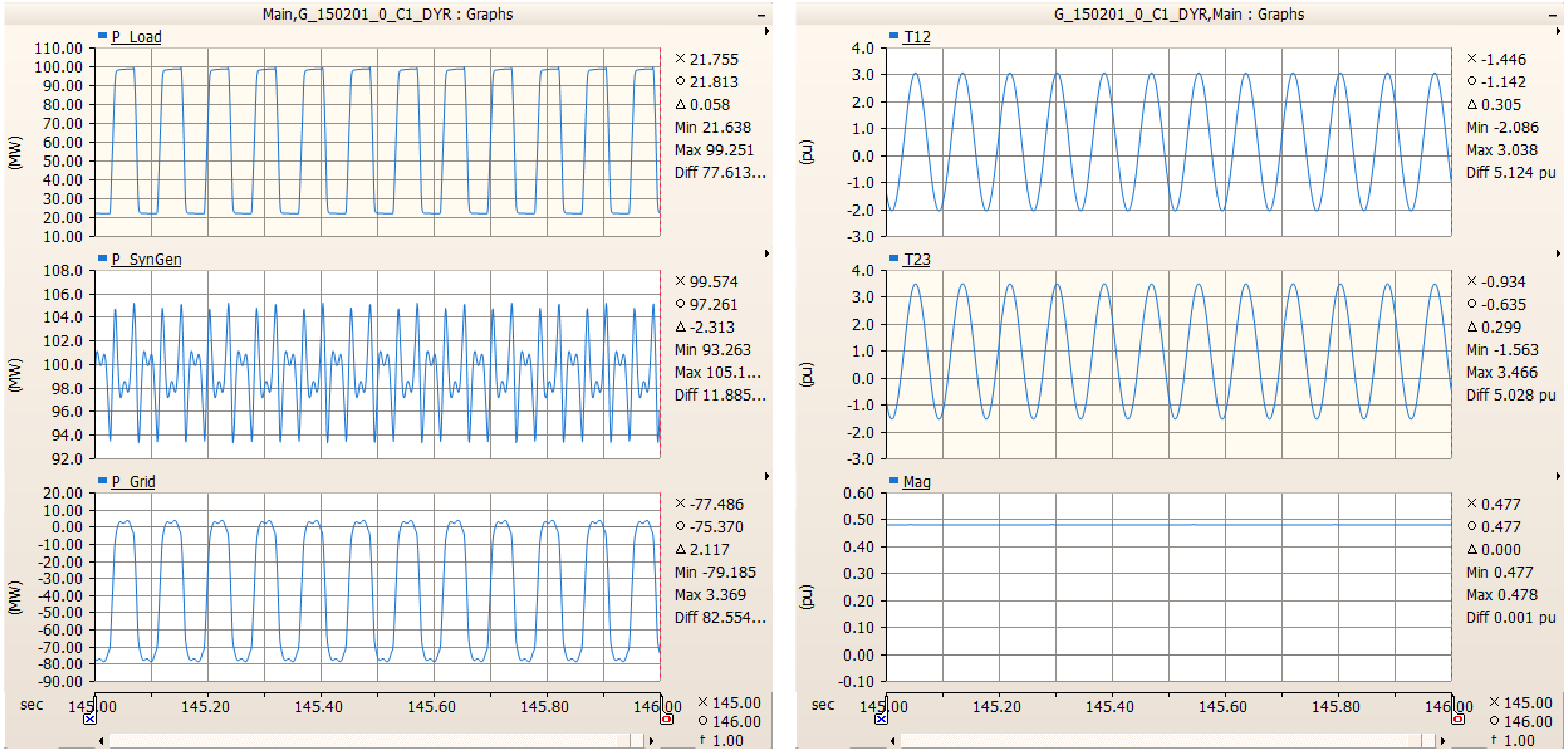


Sample Traces – S5

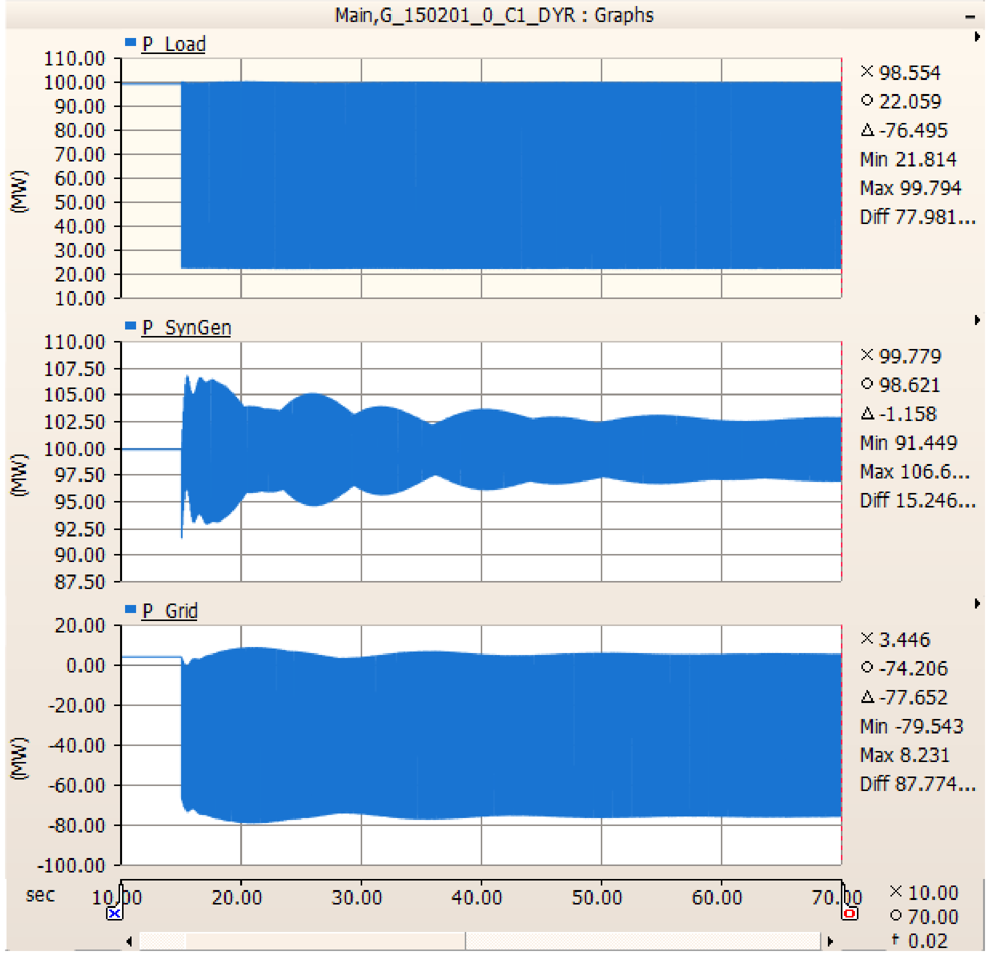


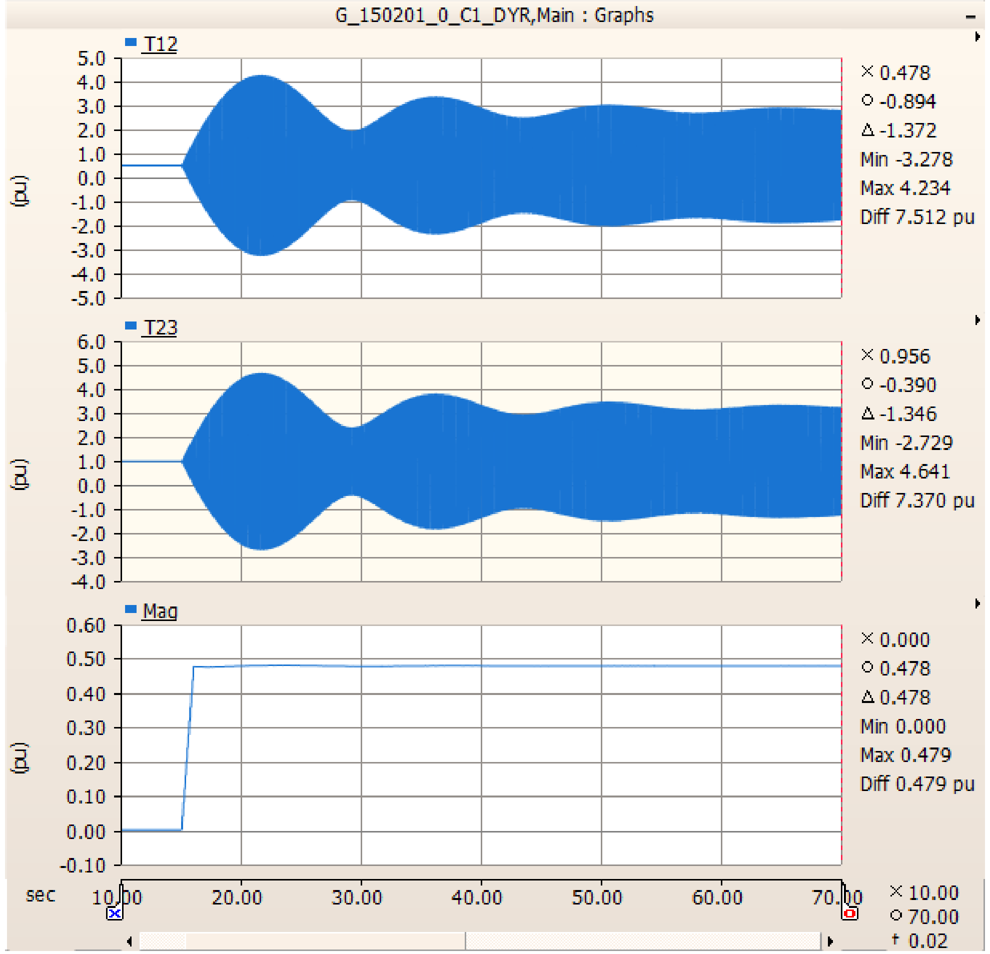


Sample Traces – S5 (Zoomed)

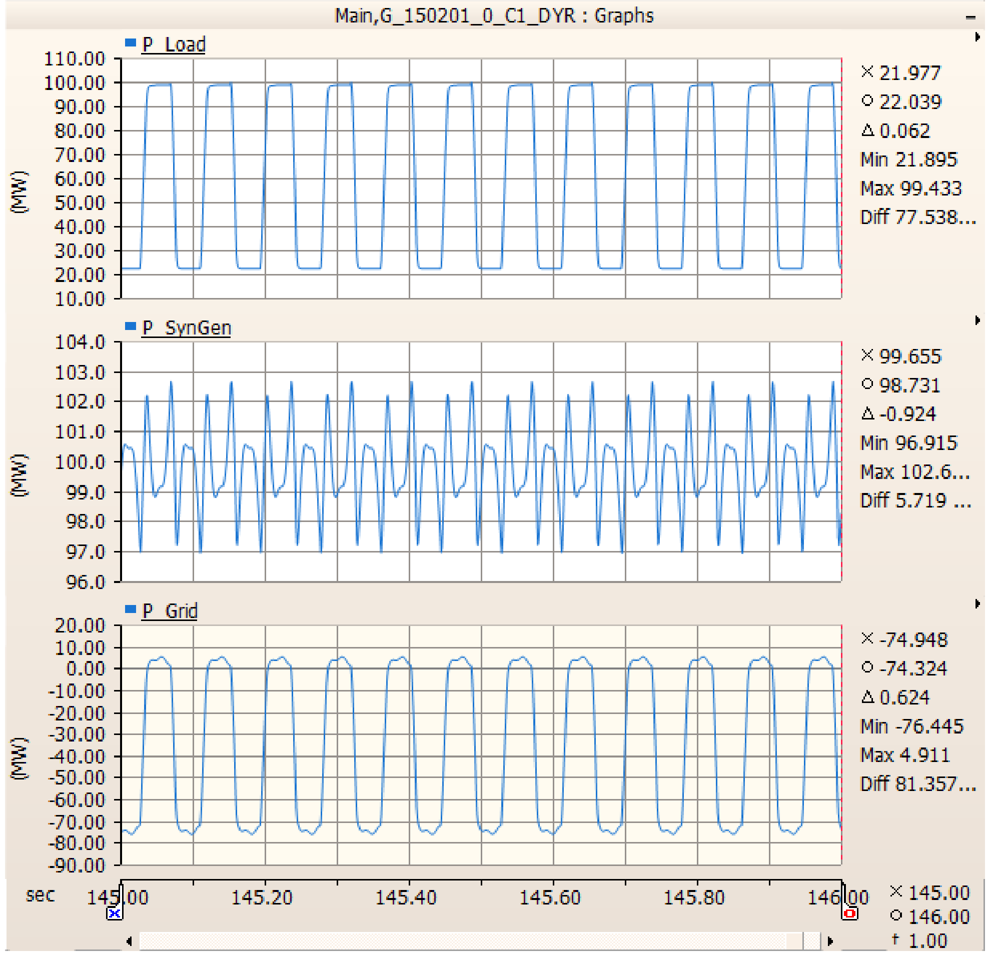


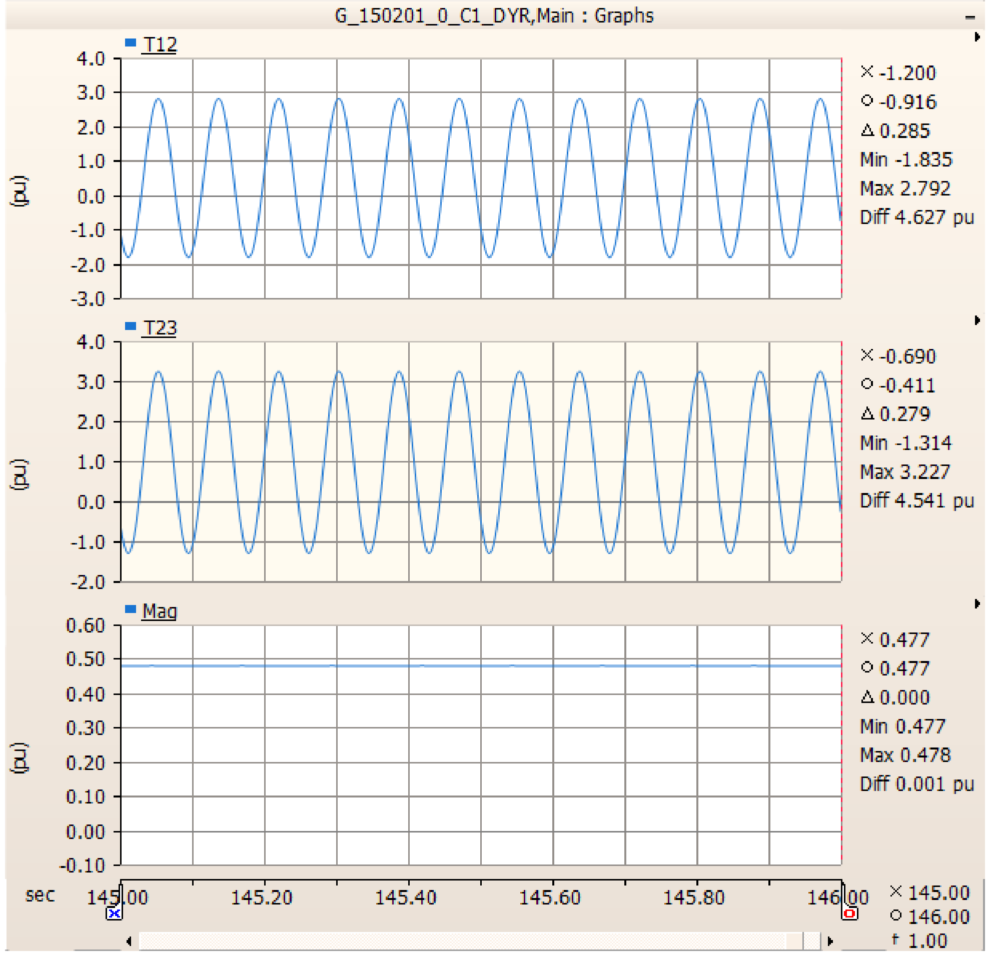
Sample Traces – S8





Sample Traces – S8 (Zoomed)





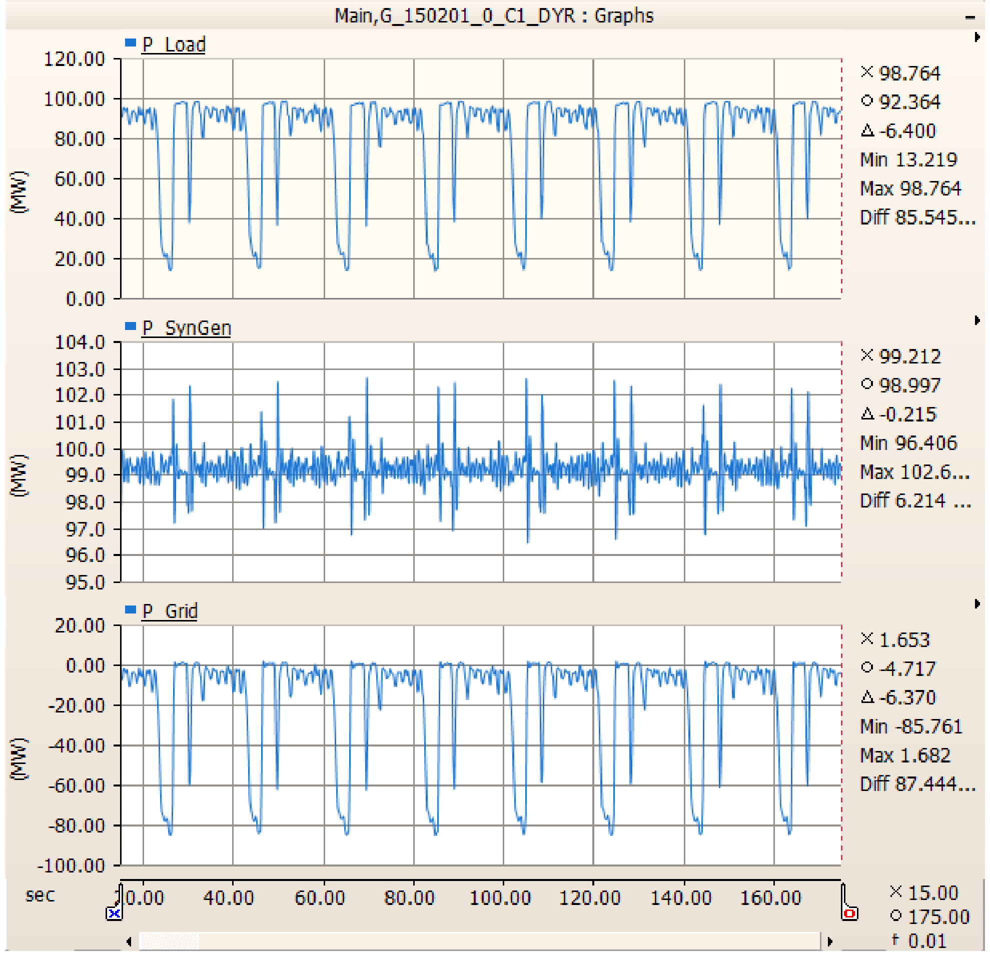
Additional Content:
Proxy AI Training Load Profile

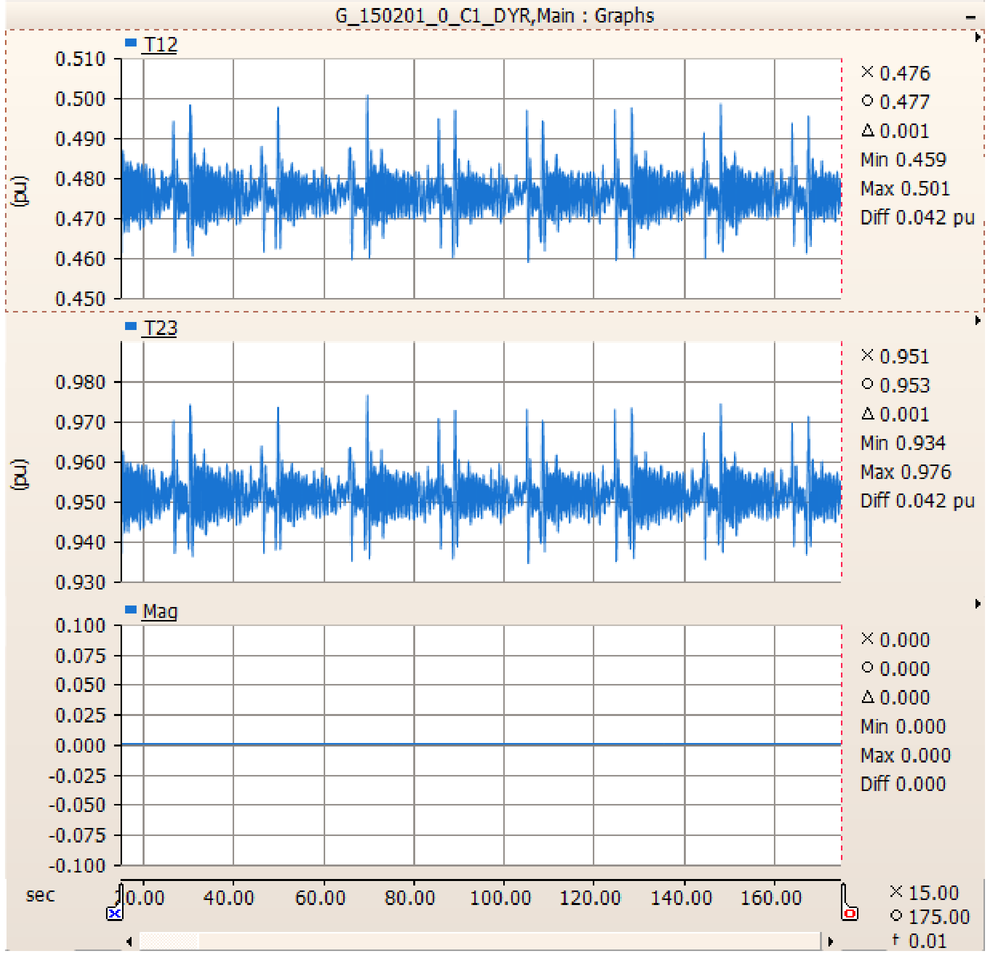
Results – Proxy AI Training Load Profile

Scenario No.	Load Variation	Impedance		Active Power Variation			Alternating Torque	
		Grid (Zg)	GenTie (Zm)	At the Load (ΔPl)	At the Machine (ΔPm)	At the Grid (ΔPg)	Tau12 (pu)	Tau23 (pu)
	Hz	pu	pu	MW	MW	MW		
S9	Measured	0.100	0.000	85.55	6.21	87.44	0.042	0.042
S10	Measured	0.100	0.050	85.42	6.05	88.06	0.040	0.041
S11	Measured	0.100	0.100	85.34	5.88	88.32	0.041	0.041
S12	Measured	0.100	0.250	85.14	5.34	88.31	0.034	0.034
S13	Measured + 12 Hz	0.100	0.000	88.86	8.09	92.22	0.993	0.974
S14	Measured + 12 Hz	0.100	0.050	88.68	7.41	91.85	1.117	1.096
S15	Measured + 12 Hz	0.100	0.100	88.66	7.38	91.34	1.146	1.124
S16	Measured + 12 Hz	0.100	0.250	88.67	6.83	91.30	0.980	0.962

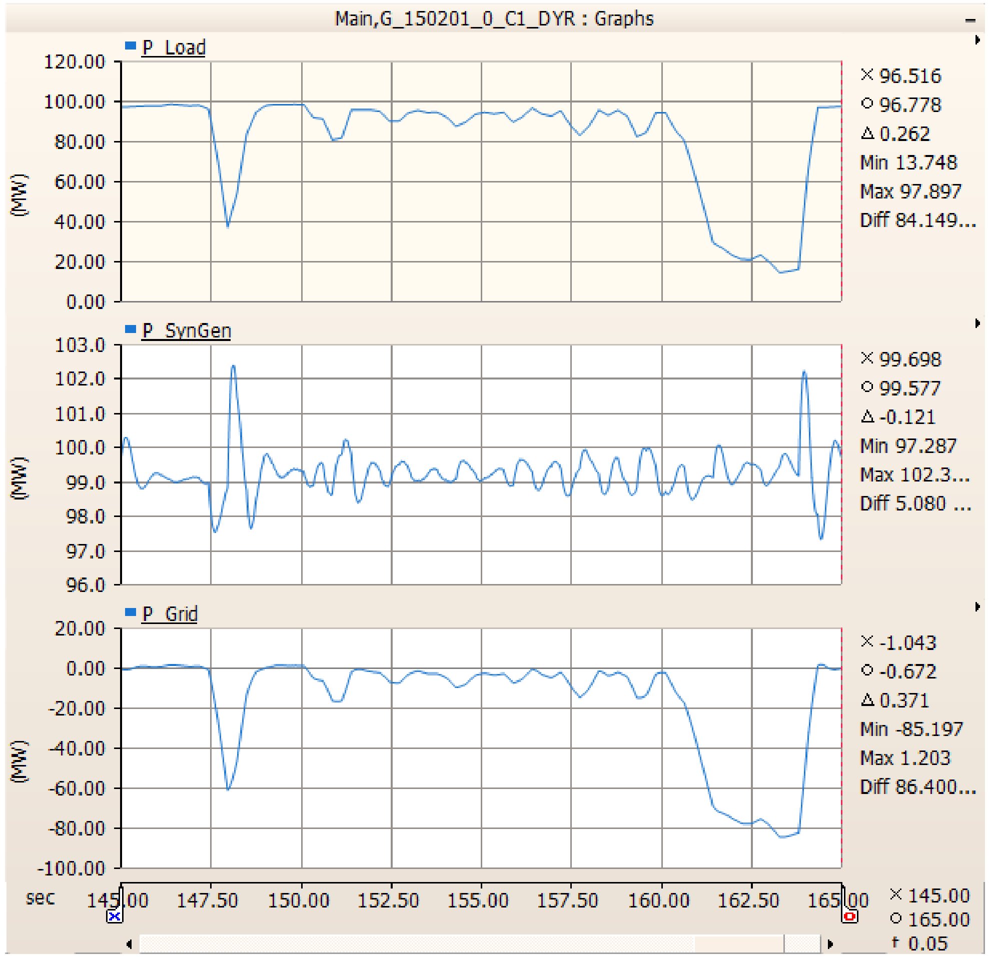
Note: All pu values are based on 100 MVA

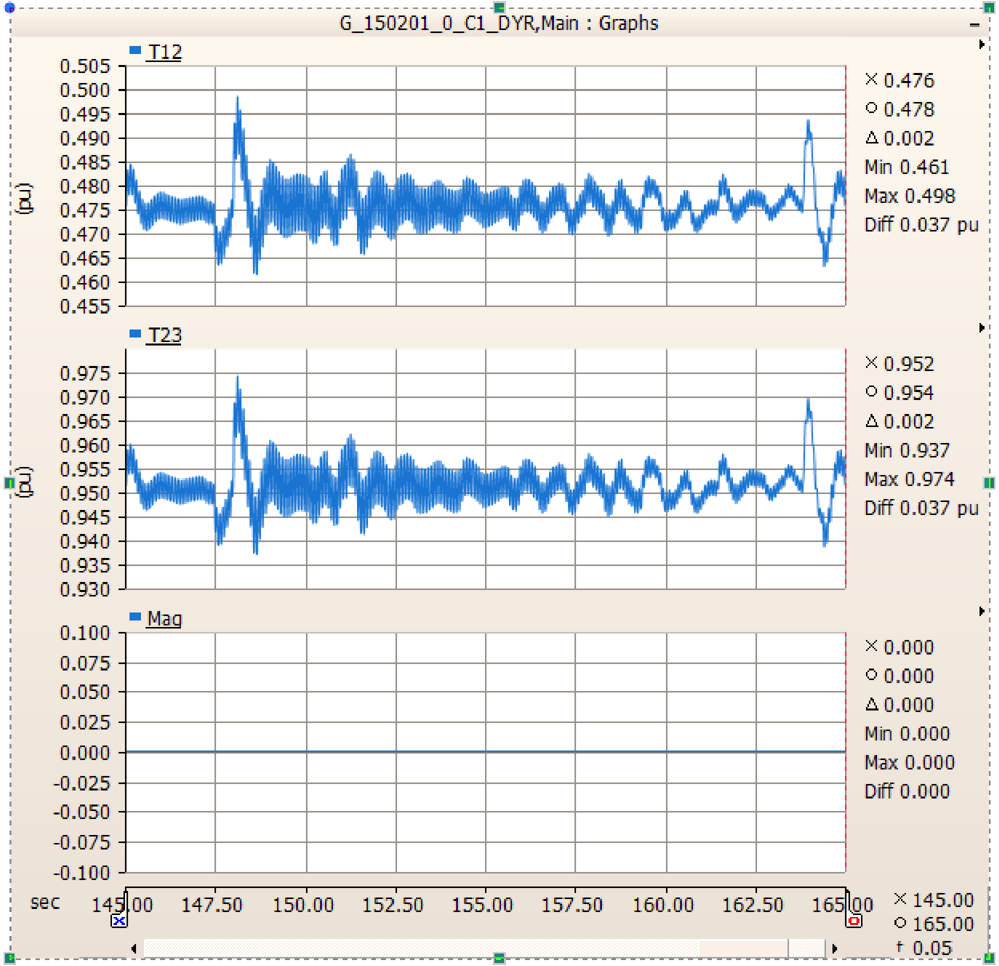
Sample Traces – S9



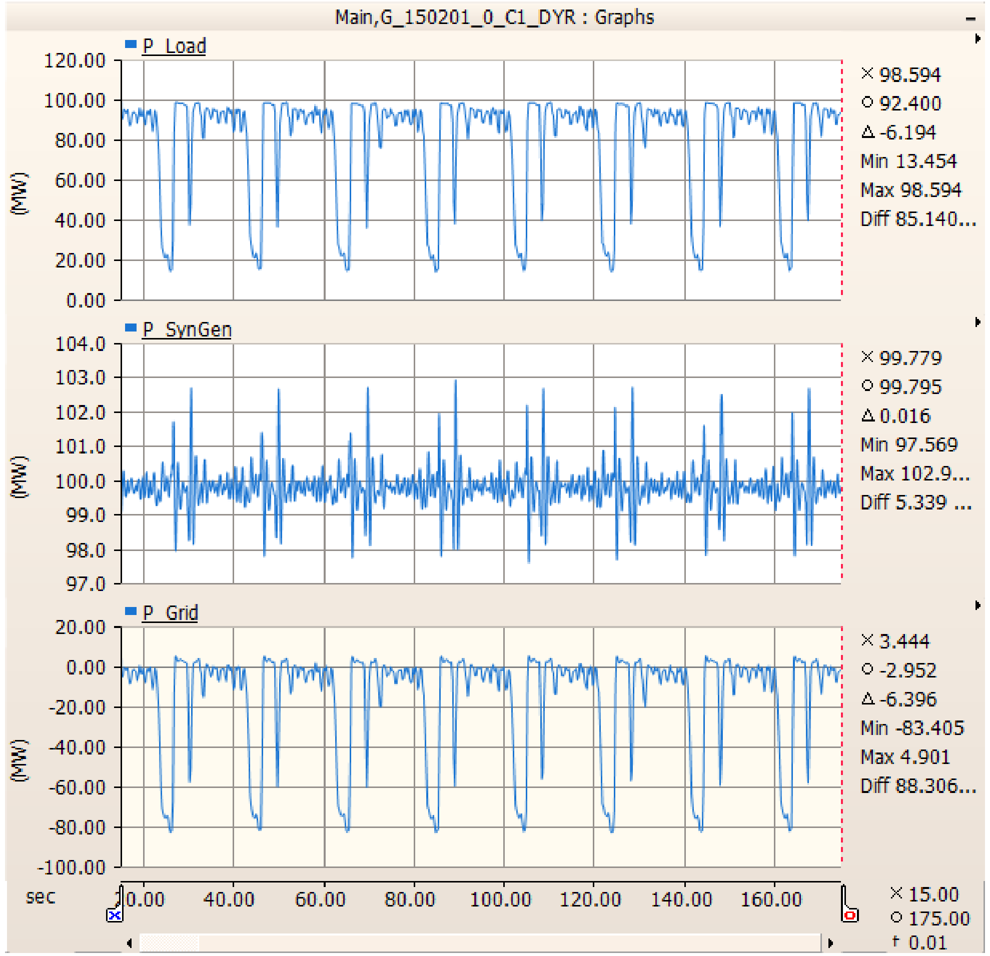


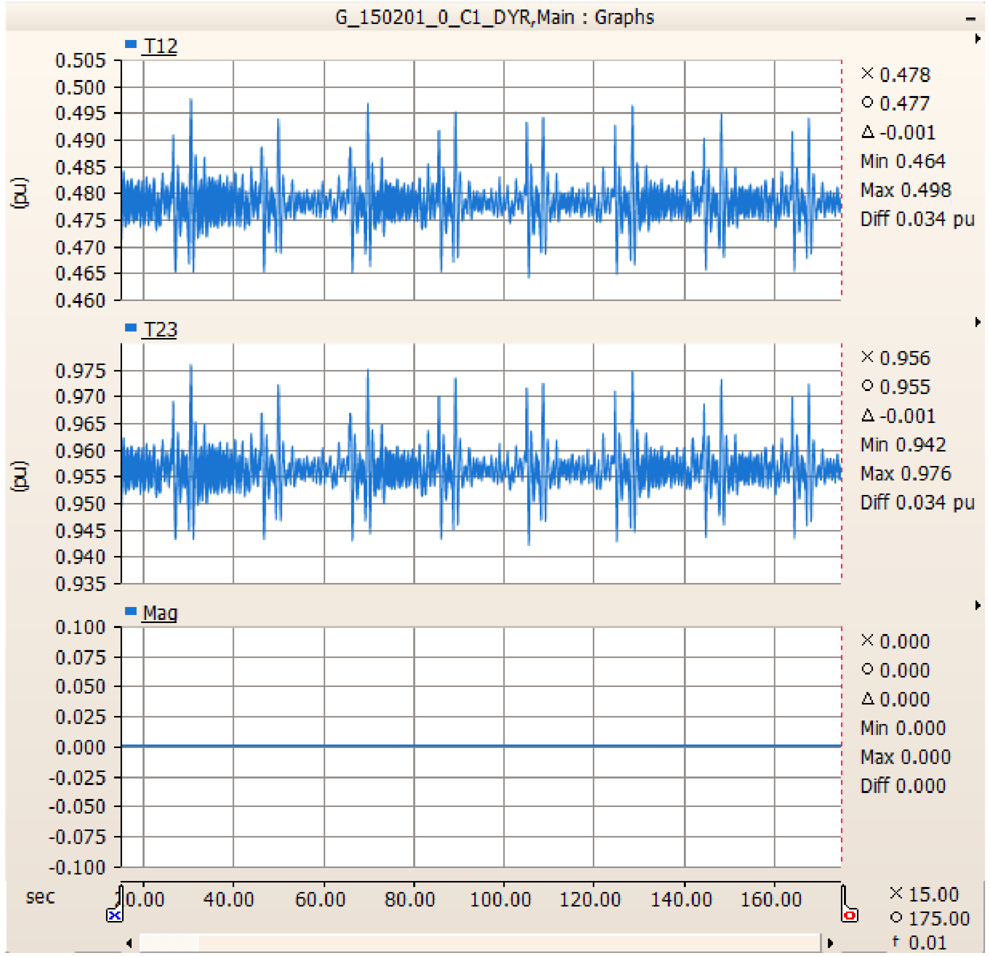
Sample Traces – S9 (Zoomed)



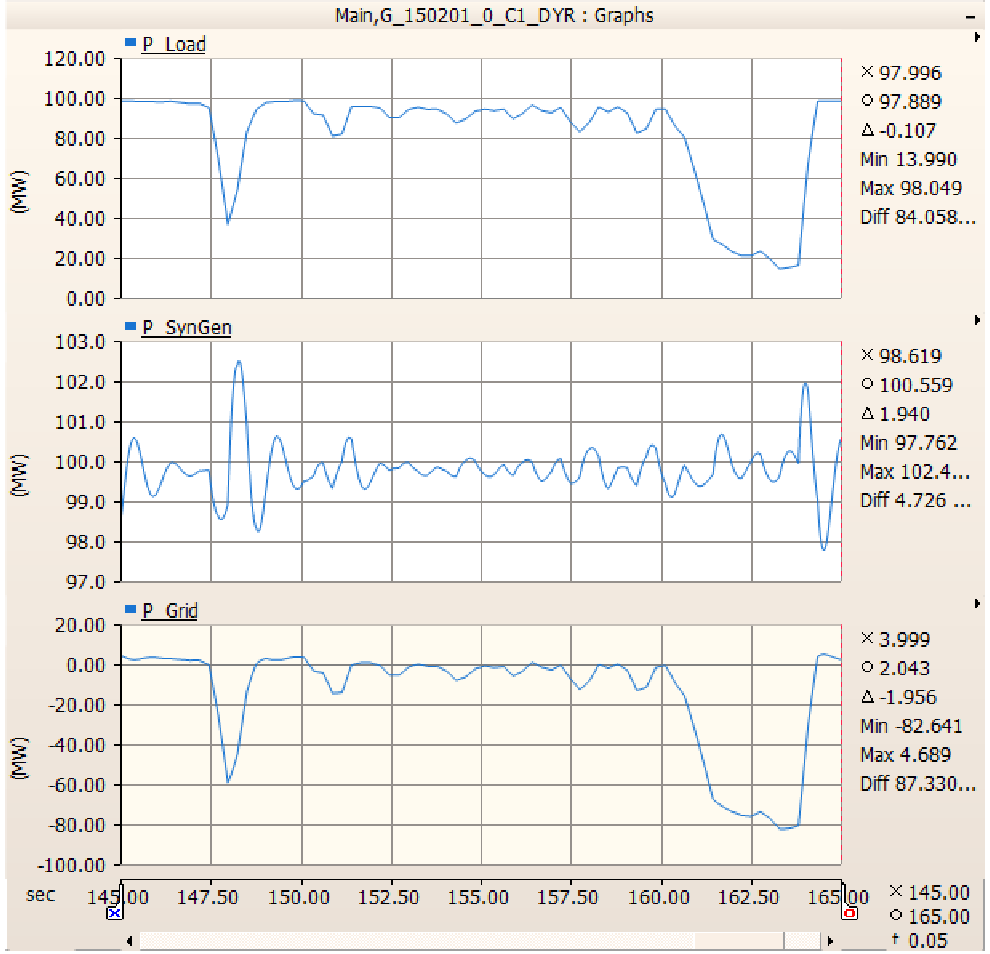


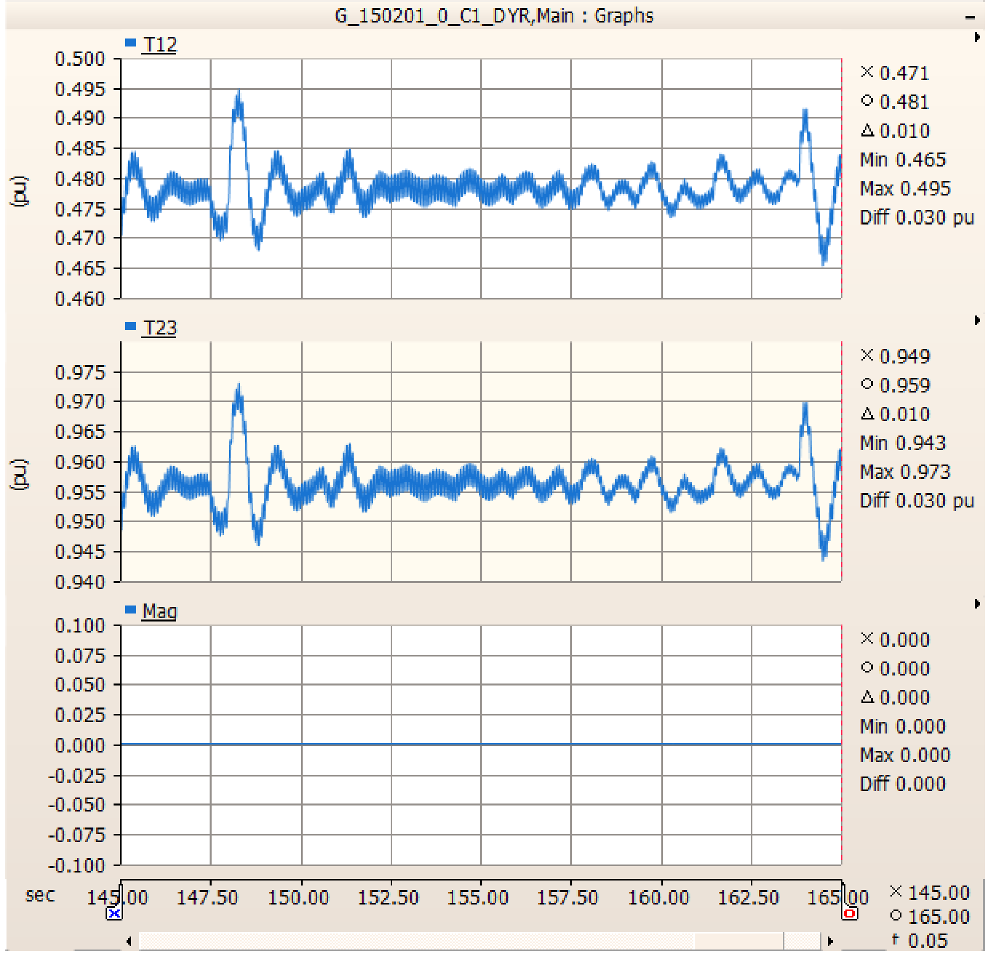
Sample Traces – S12



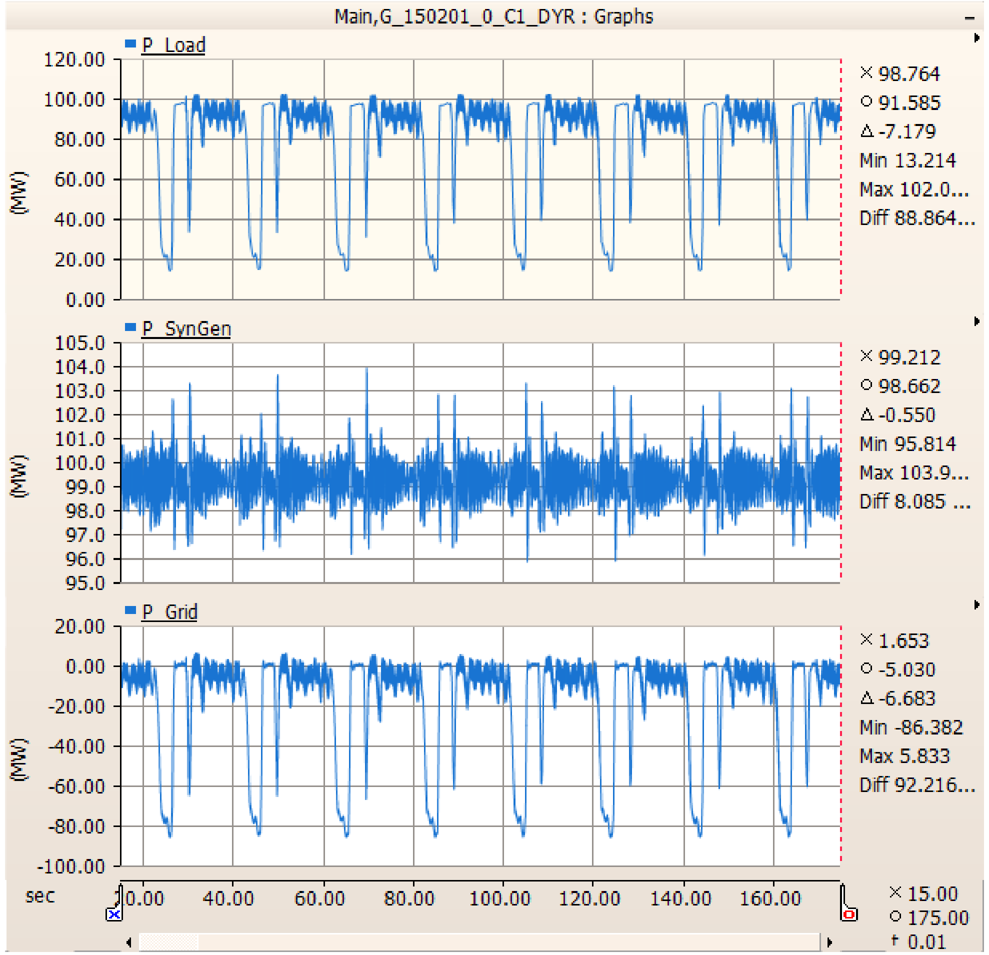


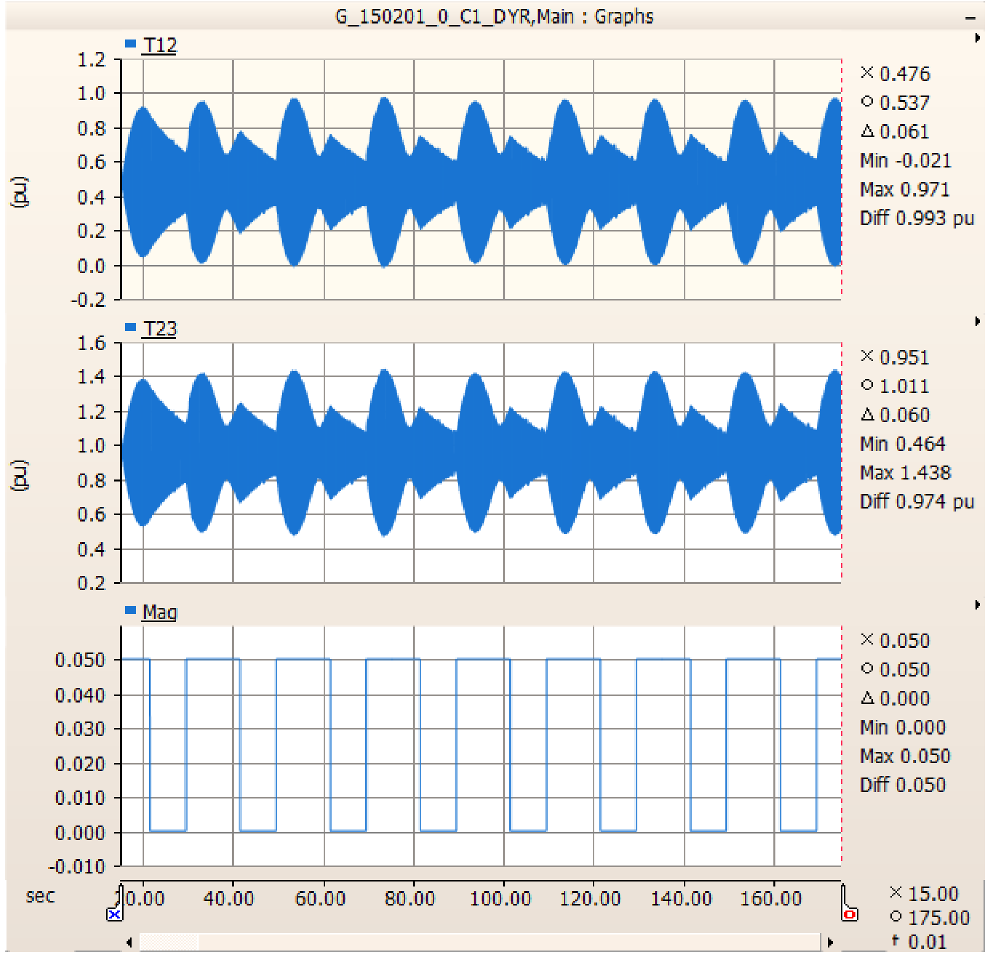
Sample Traces – S12 (Zoomed)



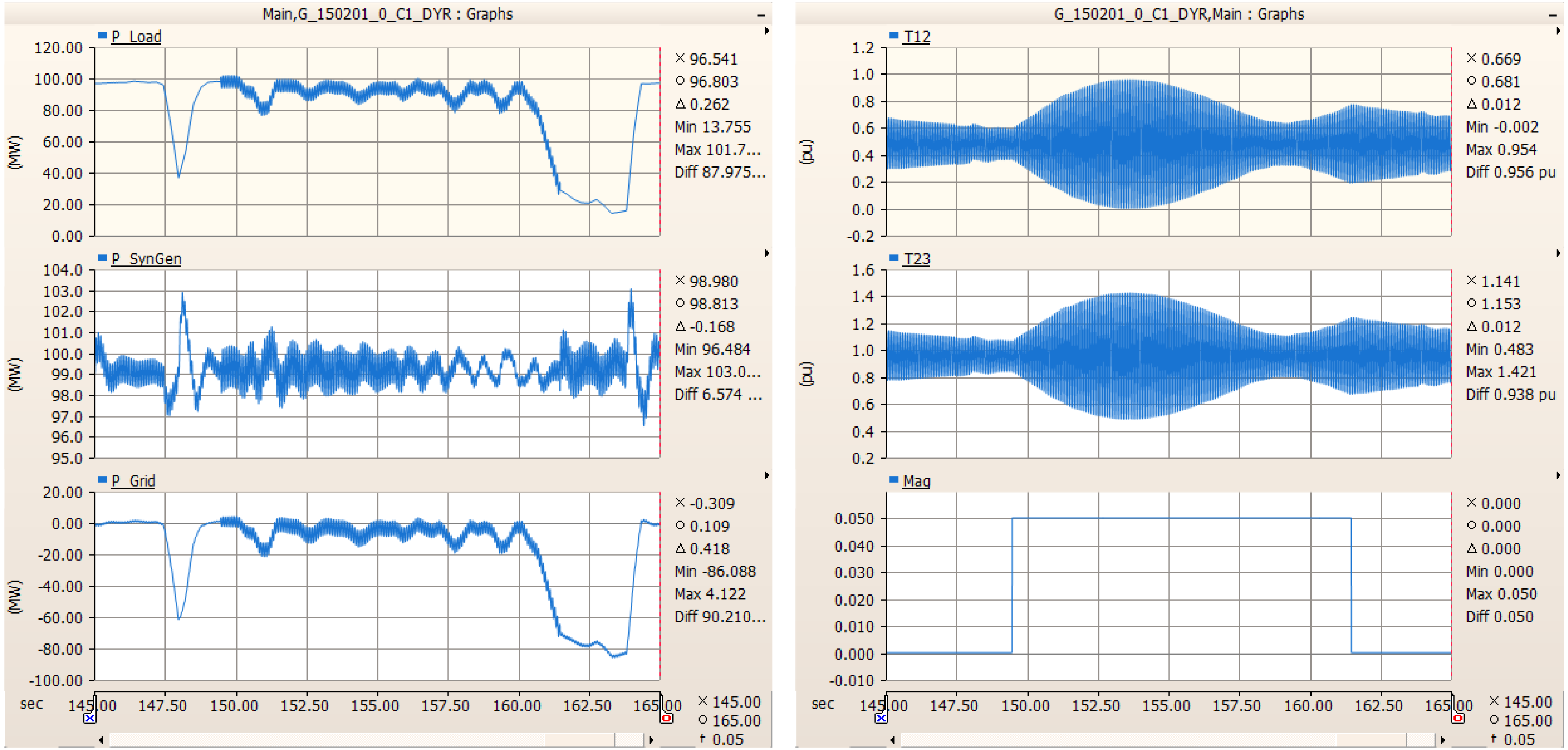


Sample Traces – S13

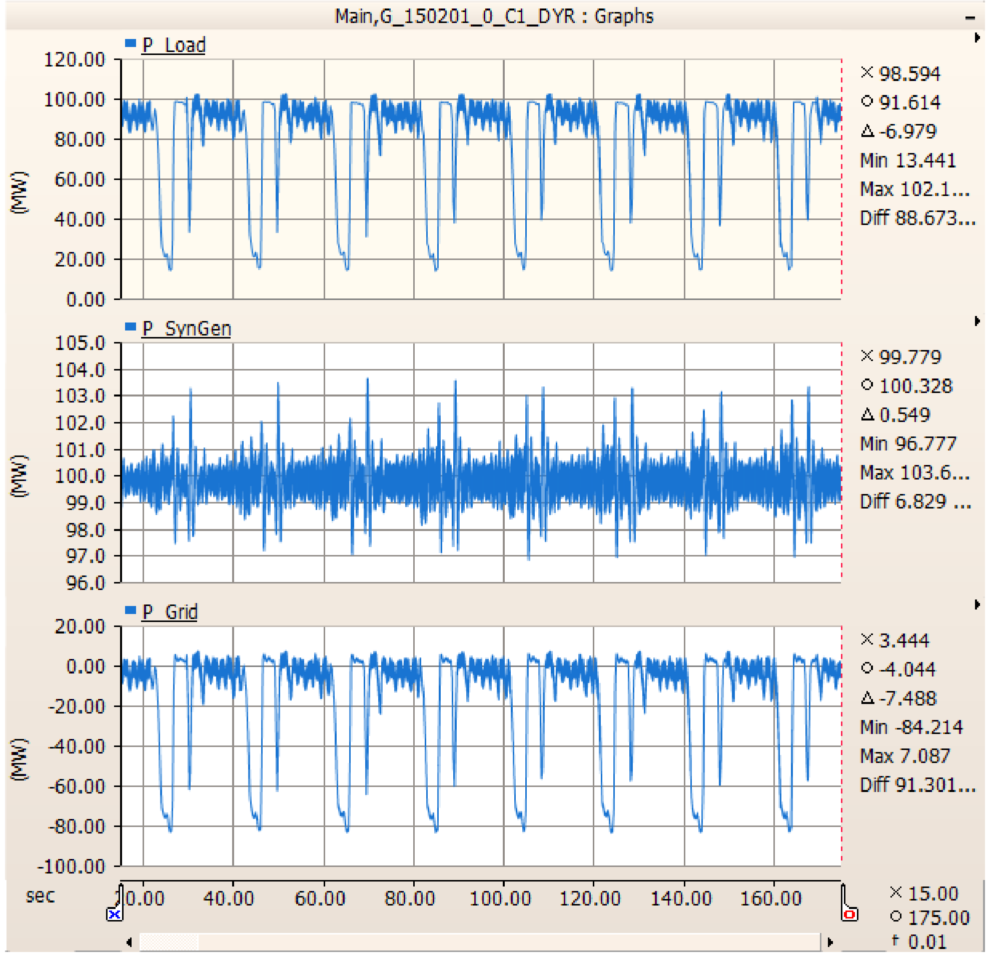


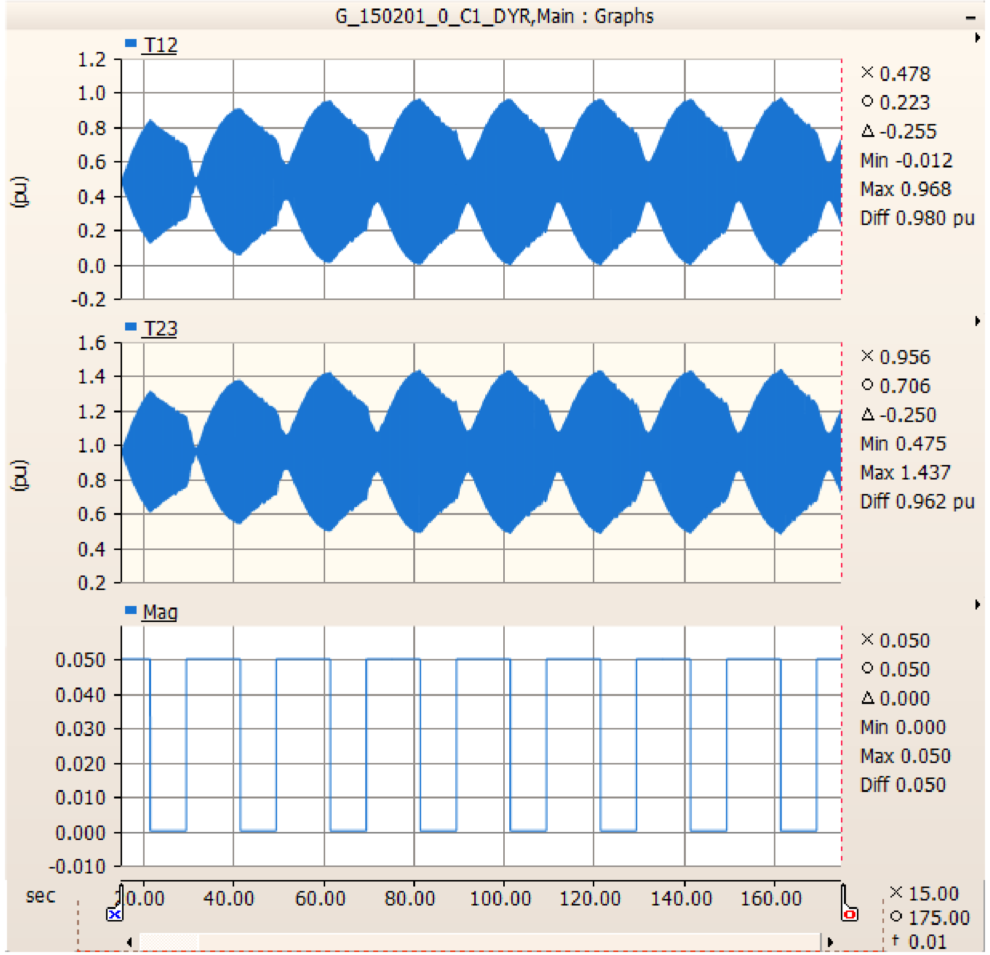


Sample Traces – S13 (Zoomed)



Sample Traces – S16





Sample Traces – S16 (Zoomed)