



2024 EMTP User Conference

Evaluation of 3rd Order Harmonics in Microgrids
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Abstract

- *The implementation of distributed generation sources with islanding microgrid capabilities can introduce new challenges for engineers integrating new large generators to existing power systems. The generator interconnection transformer winding configuration and the generator winding pitch greatly impacts the flow of circulating currents and can result in unexpected generator heating as well as high grounding resistor operating temperatures.*
- *This presentation presents a case study of the flow of 3rd order harmonic currents in a microgrid power system and how EMTP was used to design equipment modifications necessary to reduce the current. A review of generators and how they can lead to 3rd order harmonic current generation and additional options for correcting this condition will be presented.*

Goals and Objectives

During design and particularly during construction, last minute changes and/or oversights can result in unintended results. Often these result from “Value Engineering” efforts intended to reduce costs.

After this presentation you should be able to:

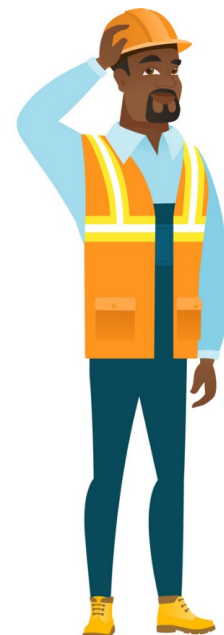
- Identify a few changes that can make big differences in system performance
- Identify when generators can be subject to high 3rd order harmonic currents
- Understand recommended practices and measures to correct the system if needed



$$I_0 = \frac{I_a + I_b + I_c}{3}$$

Introduction – Why is this important?

- Is there a problem?
- 5 recent projects 0.8 – 14MW
- Different interconnection types
 - All are three phase, three wire connection types
- All grid parallel operation
- Common symptom:
 - Current Flow in the Neutral (Ground Conductor)
 - Alarms and/or Tripping (4 out of 5)
- 5 different installers and engineers offer little assistance in resolution or opinions to correct



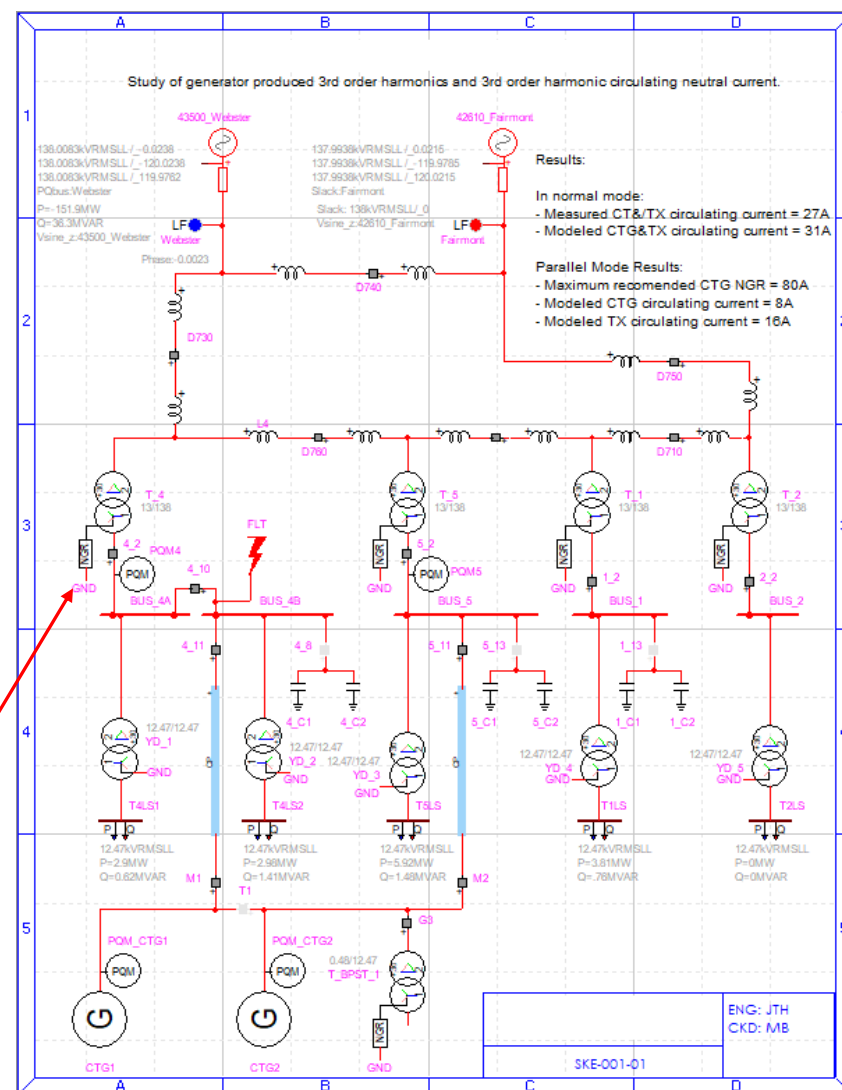
Sample Project Listing

Project Size (MW)	GSU XFMR Connection Type	Neutral / Ground Current Observed	NGR Overheating	Generator Pitch	Cause	Tripping	Resolution
0.8	Yg-Yg	Yes	N/A	2/3	Single Phase Utility Loads	Yes – 50/51G	Transformer Replacement
2	Yg-Yg	Yes	N/A	2/3	Single Phase Utility Loads	Yes – 50/51G, 46	Utility Re-Distribution of Loads & Settings Changes
3.2	Yg-Yg	Yes	N/A	2/3	Single Phase Utility Loads	No	None (Current Remains)
11	Direct Connect	Yes	Yes	4/5	3rd Order Harmonics	Alarm Only	Increase NGR Ohms
14	Direct Connect	Yes	Yes	4/5	3 rd Order Harmonics	Alarm Only	None (NGR Overheating)

There are many items that could be discussed but we are focusing on project number 4.

Project Summary

- 11MW CHP System (2 x 5.6MW)
 - Directly connected 12.47kV
 - 60Hz
 - 4/5 pitch
 - 400A NGR
- 15MVA Main Transformers
 - D-Yg
 - 1000A NGR
- Issues
 - Generator NGR is extremely hot (180C - Safety Issue)
 - Elevated Generator Winding temps (Control System Alarm)
 - Client notices “Ground Current”



Project Review

- NGR Review
 - NGR enclosure
 - Located in Ele Room
 - High temp burning hazard
- Metering Review
 - No ground fault current
 - High triplen harmonics
- Generator Review
 - Winding temps “higher than normal”

*Need to understand 3rd order harmonics....
Where do they come from, and how can we
fix this...?*

SEL-700G
2B-CTG1

Date: 12/20/2017 Time: 11:10:08.452
Time Source: Internal

	IAX	IBX	ICX	IGX	IIX	SI2X
Mag (A pri.)	250.9	251.8	257.1	2.7	253.2	10.1
Angle (deg)	-17.2	101.7	-138.1	163.8	-17.9	97.4

	IAY	IBY	ICY	IGY	I1Y	SI2Y
Mag (A pri.)	253.0	254.6	257.9	7.0	255.1	14.9
Angle (deg)	162.0	-79.8	42.8	155.2	161.7	-39.0

IN

Mag (A pri.)	0.0
Angle (deg)	106.9

	VAX	VBX	VCX	VGX	V1X	SV2X
Mag (V pri.)	7557.0	7552.5	7542.7	5.0	7550.7	27.1
Angle (deg)	0.0	120.1	-120.0	149.6	0.0	-31.9

CTG_24-1
METER

Date: 12/20/17 Time: 11:08:58.052
Time Source: int

3FX
5458
1766
5736
0.95
LAG

Fundamental Frequency = 60.0

Harmonic	IA	IB	IC	IN	VA	VB	VC
2	0.088%	0.049%	0.068%	1.367%	0.010%	0.010%	0.000%
3	3.281%	2.881%	3.564%	1683.555%	3.447%	3.398%	3.428%
4	0.000%	0.000%	0.000%	1.367%	0.010%	0.000%	0.000%
5	1.855%	1.846%	1.855%	5.479%	0.850%	0.869%	0.898%
6	0.000%	0.000%	0.000%	4.102%	0.000%	0.010%	0.000%
7	0.283%	0.332%	0.322%	0.000%	0.654%	0.605%	0.615%
8	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
9	0.127%	0.117%	0.107%	64.375%	0.283%	0.273%	0.244%
10	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.010%
11	0.059%	0.049%	0.049%	1.367%	0.205%	0.195%	0.215%
12	0.000%	0.000%	0.000%	1.367%	0.010%	0.010%	0.000%
13	0.039%	0.039%	0.029%	0.000%	0.049%	0.088%	0.098%
14	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.010%
15	0.078%	0.068%	0.059%	36.982%	0.137%	0.137%	0.117%
THD	3.75%	3.41%	4.00%	0.00%	3.59%	3.53%	3.56%
THDG	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

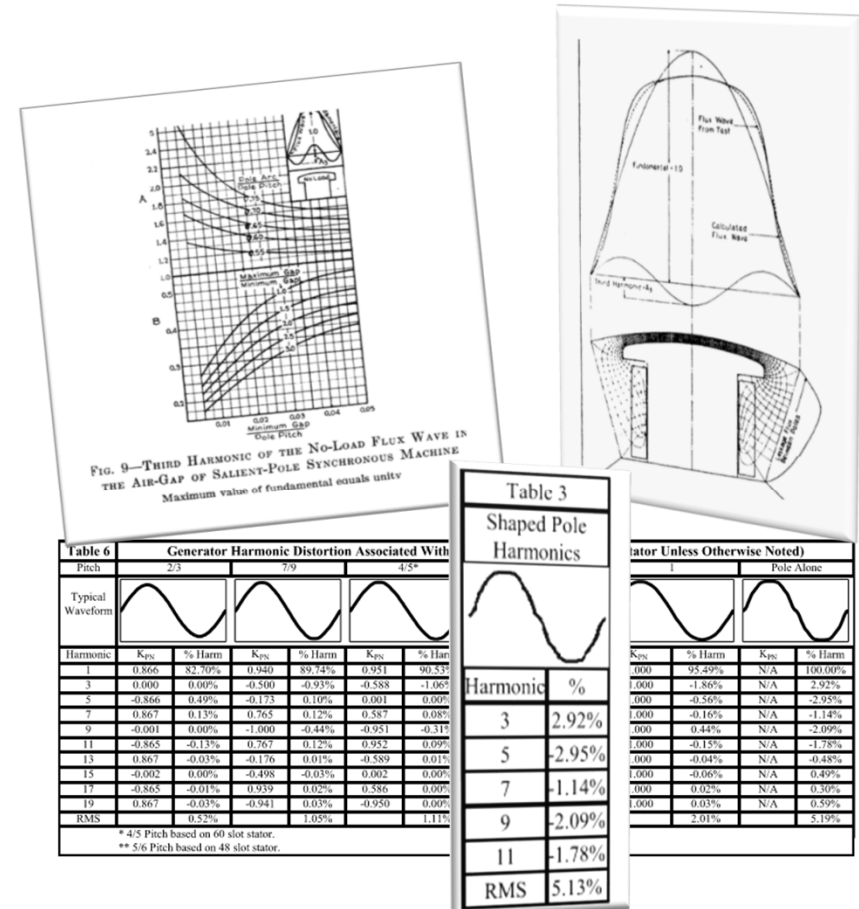
3rd Order harmonics – A Quick Review

Is this a new problem? No..

- 1898 -Potier's translation of Maxwell's treatise.
- 1927 – Wieseman Graphically demonstrates that Pole Arc / Pole Pitch = 0.67 will produce Zero 3rd Order Harmonics
- 1956 – Oldenkamp Compares 3rd order harmonic voltage calcs to tests.
- 2009 – Cardinal Plots harmonic content for various pitch styles

The shape of the rotor heads influences the voltage waveform. Shaping the pole reduces efficiency and changes the harmonic voltage content.

A fundamental function of the generator pitch.



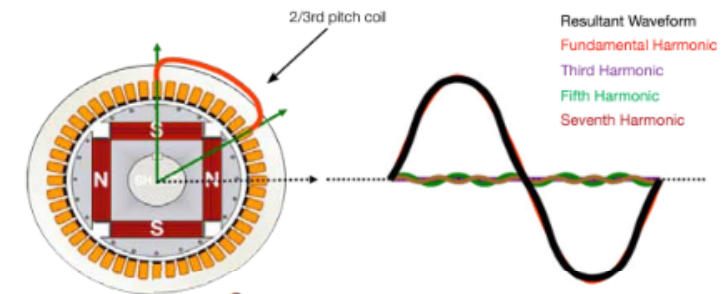
Generator Pitch

“Because of standardization, pitch requirements may be omitted from generator specifications. Familiarization with generator pitch can therefore come as a crash course after equipment data sheets....” – Cardinal

- A few things to consider – 2/3 Pitch Generators;
 - Have no 3rd order harmonics
 - Are more \$ and practically unavailable at large size (>2.5MW)
 - Are less efficient (minimally)
 - If you are not specifying a pitch... You get what you get.
- The time to study the importance of this topic is prior to specifying the units, not during construction.

(iii) Short 2/3rd winding pitch

This winding pitch equals to 2/3rd of full pitch, Figure 3.
For 48 slot = 2/3rd of 12 slots = 8 slots (coils span 1 - 9)

[illegible]

If Pitch is so important it must be in big red letters...?

Oh
No..

Why Does This Matter?

“While the fundamental frequency voltages in the three phases are displaced 120 electrical degrees in time-phase, the third harmonic voltages are displaced $3 \times 120 = 360$ electrical degrees. Thus the three third harmonic phase voltages are in phase with each other and their effect is felt only in the zero sequence circuit where it appears in the form of a circulating current at the third harmonic frequency.” – Powell 1973

- Similar enough to transformer
- Direct Connected Gen
 - Yg Gen to Yg Utility XFRMR
- Adding GSU (Yg-D) eliminates the path for current
- Unless we have 2/3 pitch Gen there will be the potential for circulating 3rd harmonics.

Connection		Equivalent Circuit/Admittance Matrix		
Bus P	Bus S	Positive	Negative	Zero
		P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
		P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
		$\begin{bmatrix} y_p & -y_m \angle 30 \\ -y_m \angle -30 & y_s \end{bmatrix}$	$\begin{bmatrix} y_p & -y_m \angle -30 \\ -y_m \angle 30 & y_s \end{bmatrix}$	P $\xrightarrow{y_{s.c.}}$ S
		P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
		$\begin{bmatrix} y_p & -y_m \angle 30 \\ -y_m \angle -30 & y_s \end{bmatrix}$	$\begin{bmatrix} y_p & -y_m \angle -30 \\ -y_m \angle 30 & y_s \end{bmatrix}$	P $\xrightarrow{y_{s.c.}}$ S
		P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S

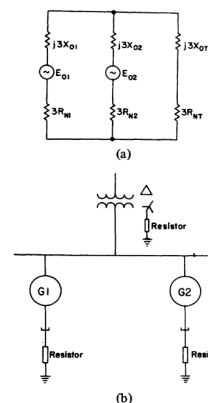


Fig. 3. (a) Individual resistance grounded power system. (b) Third harmonic zero sequence equivalent circuit.

3rd order harmonics are produced in the generator voltage waveform. Therefore the amount of current that flows in the system is dependent on the neutral grounding resistor size.

The Case for Doing Nothing

What happens if we leave this as is?

- NGR Heating
 - IEEE 32 allows a hot NGR (725F?)
 - Move NGR to a place that cannot be touched?
- Generator Heating
 - Near alarm limit continuously
 - O&M concerns
- Ground Current
 - O&M concerns
 - Heating of Transformer

Table 1: IEEE-32 Time Rating and Permissible Temperature Rises for Neutral Grounding Resistors

TIME RATING (ON TIME)	PERMISSIBLE TEMP RISE (ABOVE 30°C)
Ten Seconds (short time)	760°C
One Minute (short time)	760°C
Ten Minutes (short time)	610°C
Extended Time	610°C
Steady State (continuous)	385°C

*CSA permissible rise is 375°C over 40°C ambient on a continuous duty



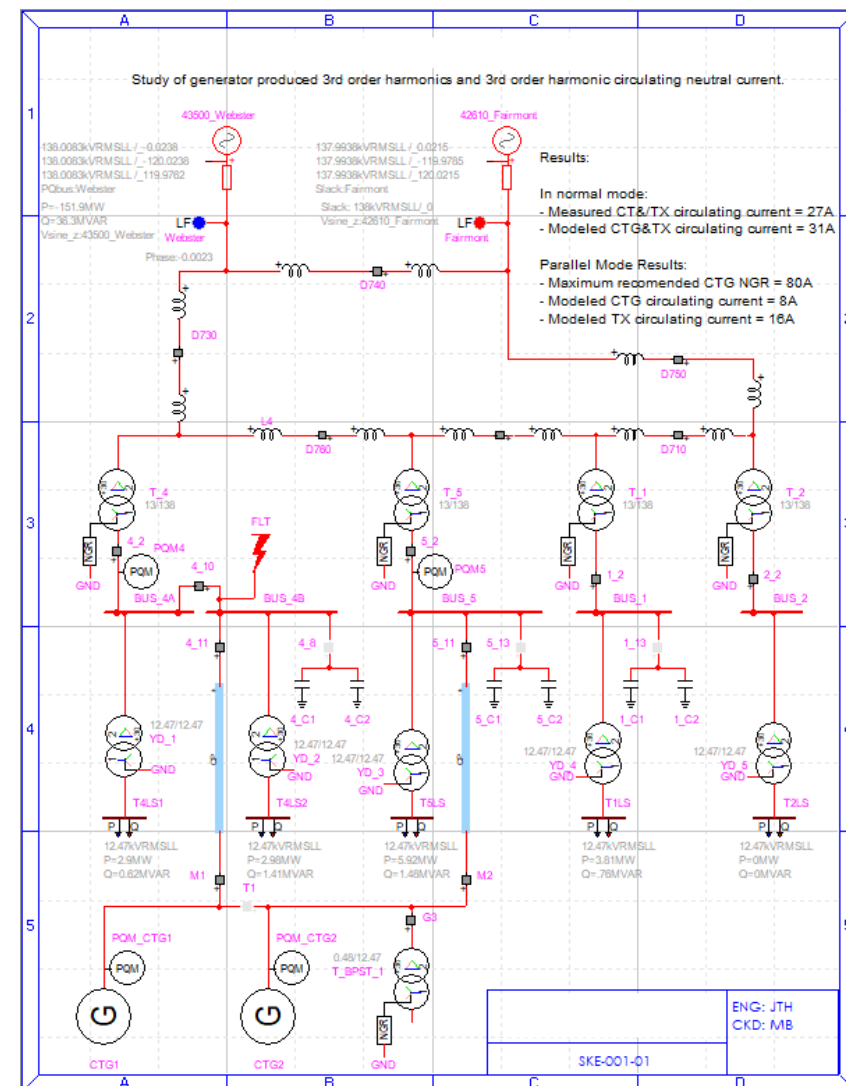
For this project, the NGRs are in an electrical room, and we could not live with high temps. Client could not live with current being metered in the substation ground.

Modeling - Intent

Why model this?

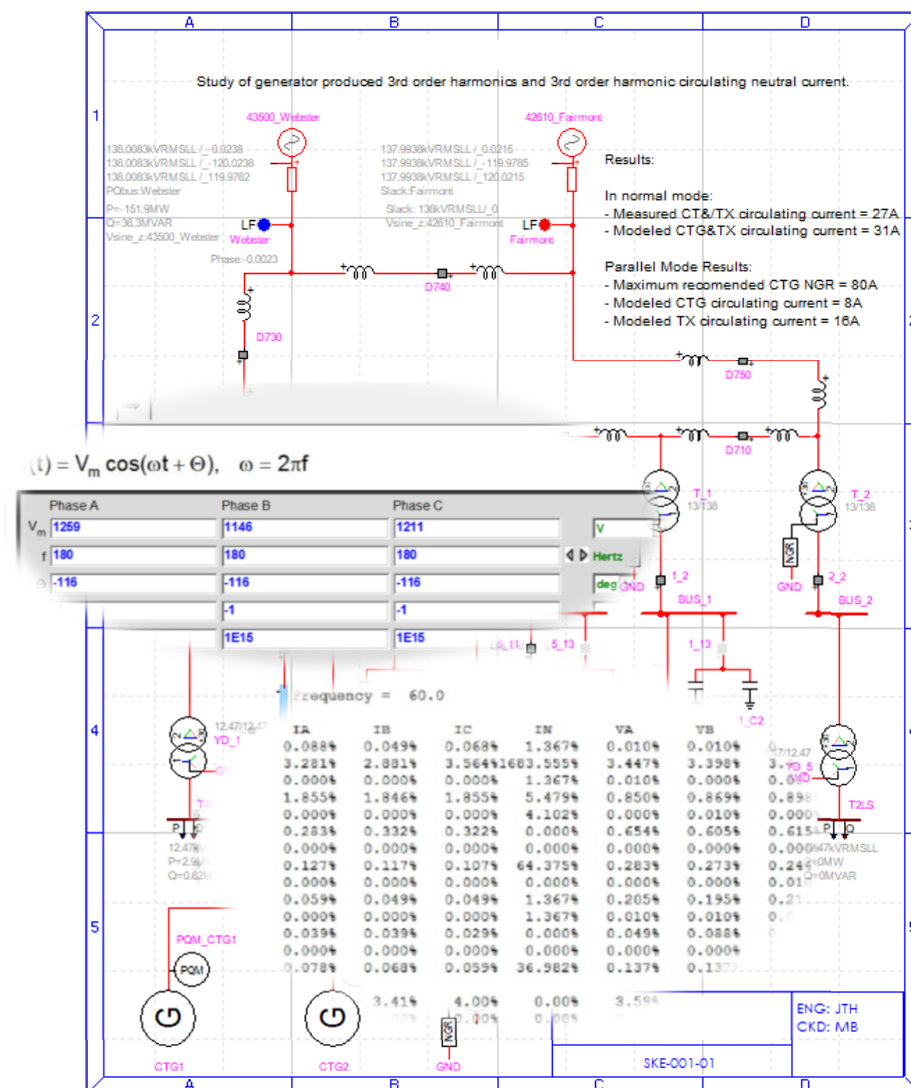
- How do we fix the issue of the circulating current?
 - Neutral Current is up to ~30A
 - Intuitively we know if the NGR is higher resistance, the current will be reduced.
 - Modeling can verify our intuition
- What level of increased NGR resistance can we tolerate and still maintain ground fault relay coordination?
 - Iterative analysis

Need to model the system as connected in the field, and also under varying NGR Ohms.



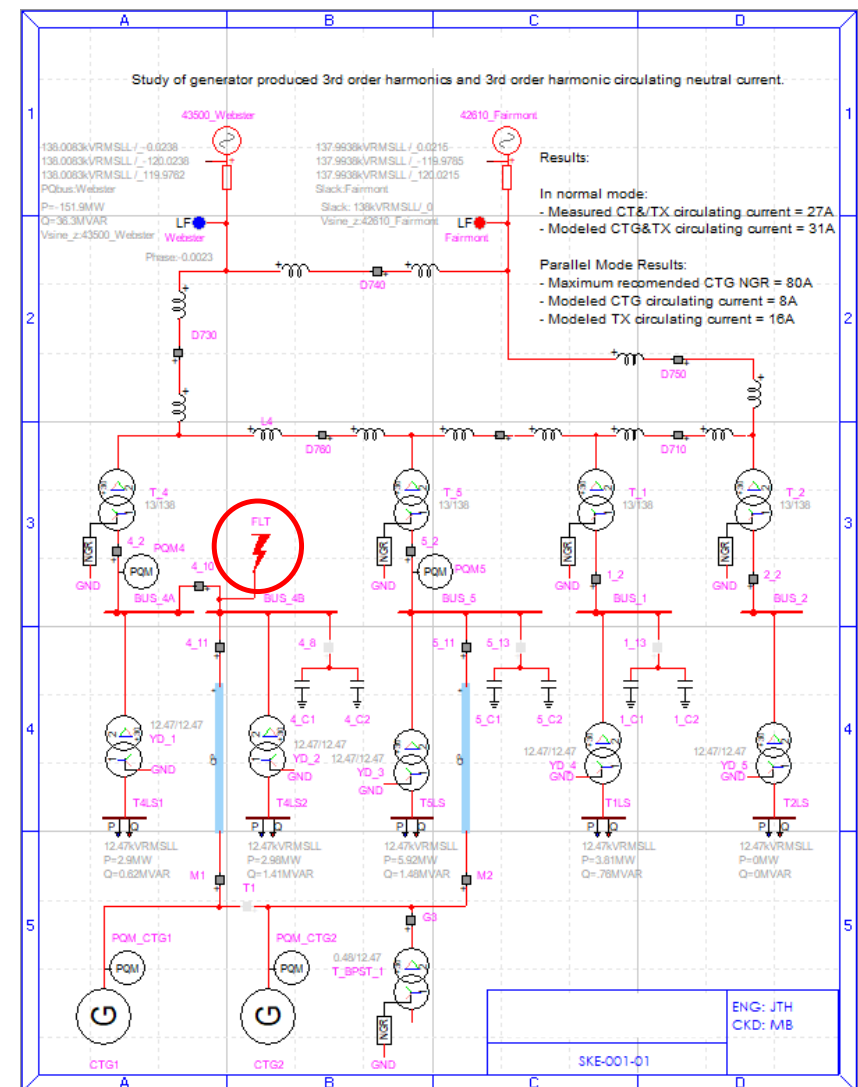
Modeling - Tuning

- Tune harmonic conditions to match meter readings at Generator and Utility
- Model configuration matches as constructed NGR configuration
 - Transformer and Turbine NGRs (1000A and 400A)
- Modeled circulating current is consistent with field observations
 - 31A vs 27A
- Allows for What-If analysis
 - Paralleling of Generators with single transformer.



Review the Design Intent

- Microgrids
 - Operate in parallel with the utility
 - Operate in island mode
- Need to Evaluate Both Modes
 - Ground fault levels >0
 - Ground fault levels $=0$
 - During both modes the required GF level should not be radically changed.
 - Protective relays
- Using EMTP for this effort
 - TOV levels
 - Fault currents
 - Harmonics



Modeling – Alternatives

- Level of circulating current varies based on the configuration
 - We can use EMTP to model many alternatives
- Team Ideas:
 - Operate Gens at higher kVA
 - Does not address the flow of harmonic current (changes % of harmonics)
 - Install GSU Transformer with Yg-D
 - Blocks zero sequence path to main transformer
 - Does not block flow between gens
 - Use Reactor instead of Resistor
 - Similar performance (but higher cost due to replacement)
 - Unground the Generators
 - Blocks zero sequence path
 - Protective Device Coordination Concerns
 - Increase the NGR Ohms
 - Reduces flow of current (both harmonic and fundamental)

Connection		Equivalent Circuit/Admittance Matrix		
Bus P	Bus S	Positive	Negative	Zero
∇	∇	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
∇	∇	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
∇	Δ	$\begin{bmatrix} y_p & -y_m \angle 30 \\ -y_m \angle -30 & y_s \end{bmatrix}$	$\begin{bmatrix} y_p & -y_m \angle -30 \\ -y_m \angle 30 & y_s \end{bmatrix}$	P $\xrightarrow{y_{s.c.}}$ S
∇	∇	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S
∇	Δ	$\begin{bmatrix} y_p & -y_m \angle 30 \\ -y_m \angle -30 & y_s \end{bmatrix}$	$\begin{bmatrix} y_p & -y_m \angle -30 \\ -y_m \angle 30 & y_s \end{bmatrix}$	P $\xrightarrow{y_{s.c.}}$ S
Δ	Δ	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S	P $\xrightarrow{y_{s.c.}}$ S

Where: P primary winding, S secondary winding, ∇ star connection, ∇ grounded star connection, Δ delta connection, and $y_p = y_s = y_m = y_{s.c.}$, where $y_{s.c.}$ is the short circuit admittance of a transformer.

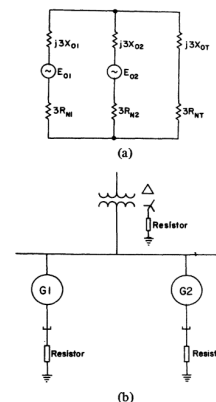
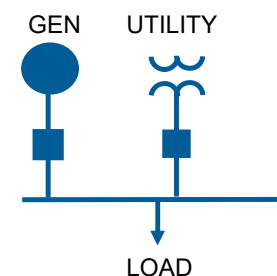


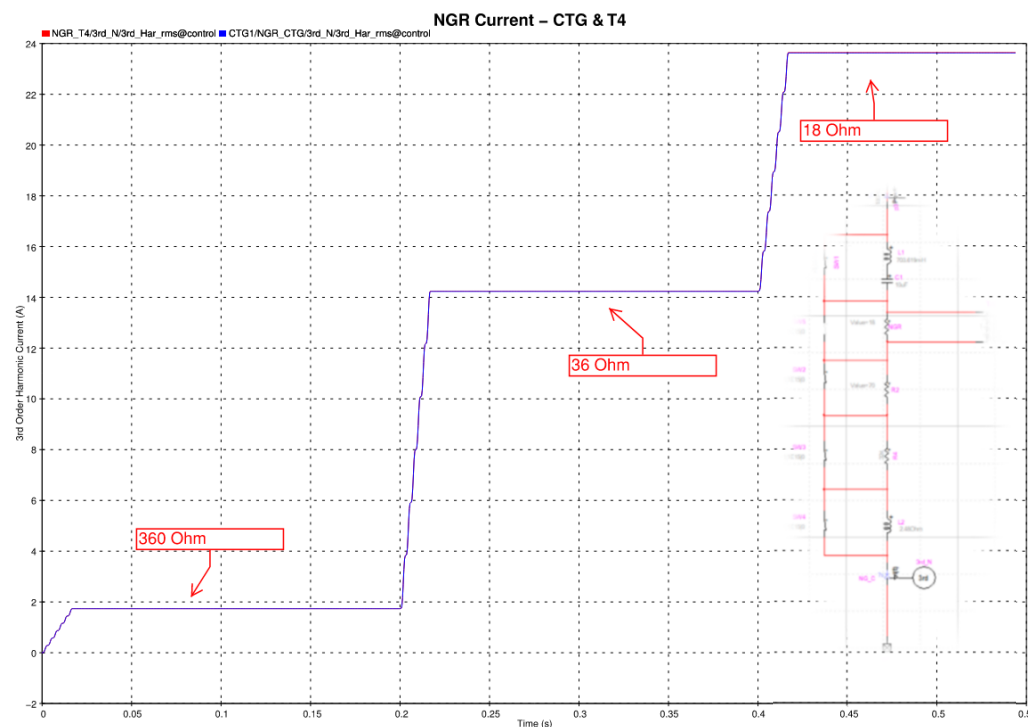
Fig. 3. (a) Individual resistance grounded power system. (b) Third harmonic zero sequence equivalent circuit.

MUST REVIEW THE DESIGN INTENT



Modeling – NGR Sensitivity

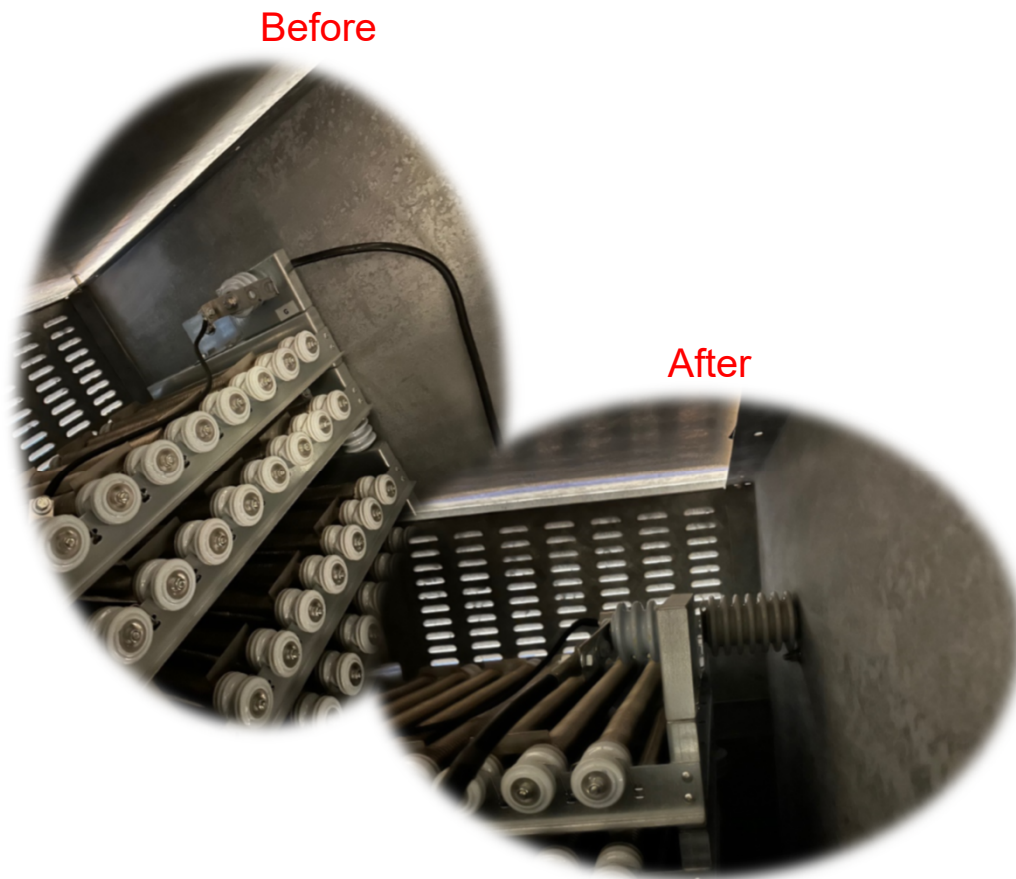
- Picking a resistance
 - Higher resistance produces lower circulating current
 - To approach zero 3rd order harmonics High Resistance Ground is needed.
- Constructability
 - High resistance grounds on 15kV equipment were not readily available
 - NGR vendor can increase resistance to 100 Ohms (80A).
 - Requires additional enclosure extensions for larger bank of resistors.
- Impact
 - Delays (Which equate to cost)
 - Installation Cost (\$50k each to fix)



In Service Situation

After O&M activities and 2 years after NGR correction

- Generator rehab and reinstallation
 - Rewound and completely refurbished
- Operator notes that NGR-2 is cool to the touch
 - Did something change with the refurbished generator?
 - NGR-1 is still warm
- Opening of the NGR shows the NGR is not connected
 - Generator was operating ungrounded



Conclusions

- During development generation system designers must review the system grounding strategy.
 - We must ensure that our plan will not impact the system protection.
- When connecting a DG system to a feeder,
 - If both the DG and utility system are configured as Wye-grounded sources, the two sources (utility and DG) will supply neutral current to the system or in resistance grounded systems will circulate triplen harmonics.
 - If the utility is weak and the generator is large the share of generator neutral current is high
 - If the system is producing triplen harmonics, current flows in all grounds
- Once a system is outlined, a careful review of the use case is needed.
 - Will we have island mode and parallel mode?

Conclusions Cont.

- If systems are grounded, and generators are not isolated by a GSU,
 - There will be triplen harmonics unless 2/3 pitch is used.
 - If the generator cannot be 2/3 pitch use high impedance grounding
- Evaluate options for hybrid grounding schemes
 - Can use high impedance ground during one mode and low or solid grounding in other modes.
 - For parallel units, consider interlocked grounding to reduce the number of units grounded while operating.

References

1. Wieseman, “Graphical Determination of Magnetic Fields Practical Applications to Salient-Pole Synchronous Machine Design”, AIEE 1927.
2. Angst/Oldenkamp, "Third-Harmonic Voltage Generation in Salient-Pole Synchronous Machines", AIEE 1956.
3. Powell, “Influence of Third Harmonic Circulating Currents in Selecting Neutral Grounding Devices”, IEEE 1973
4. Cardinal, “Generator Pitch and Associated Concerns When Paralleling Generators”, IEEE 2009
5. IGard, “Neutral Grounding Resistors”.

Thank You!



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