Study Committee C4

Power System Technical Performance

10563_2022

Analysis of Harmonic Propagation in Meshed Power Systems Using Standing Waves

Bjarne Søndergaard BUKH*[1,2]
bsbu@energy.aau.dk
ORCID: 0000-0001-5665-4757

Filipe Faria da SILVA[1]
ffs@energy.aau.dk

Claus Leth BAK[1]
clb@energy.aau.dk

Aalborg University[1] Energinet[2]

Denmark

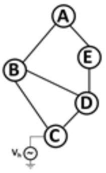
Motivation

- It is well known that the use of long underground transmission cables (UGC) causes changes in the harmonic resonances towards lower frequencies in the grid as compared to overhead lines (OHL).
- It is **difficult to explain harmonic propagation** in meshed power systems and it is of major concern that we have no proper explanation for propagation of harmonics in such systems today.
- The key issue is that **it cannot be foreseen** from simple physically based considerations how a certain **change** in topology will **affect** the overall harmonic situation.
- The basic **behaviour of** harmonic voltage **propagation in a meshed system** for both series and parallel line configuration changes is explained with **the theory of standing waves** and the expected **propagation characteristics** for these configuration changes **is explained**.
- The purpose is to explain that observed changes at a given node in a system are due to changed terminal conditions and hence, changes of standing voltage waves along the transmission lines, which is not unambiguous when observing changes at nodes only.

Method/Approach

1) Benchmark model
2) Propagation of harmonics
3) Study cases

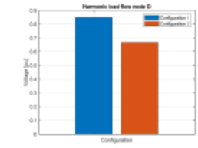
1) Benchmark model



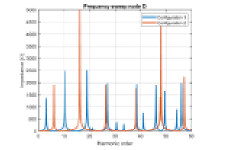
Parameter	Value		Unit
	OHL	UGC	
R	0.023599	0.018572	Ω /km
L	1.02268	0.621831	mH /km
G	0	1.376167	µS/km
C	0.01142	0.219023	µF /km

- Benchmark model with 5 substations A, B, C, D and E and a single harmonic source are used.
- Connected with at least two lines with specific parameters for OHL and UGC. Equal line length (90 km).

2) Propagation of harmonics



20th Harmonic voltage at 'D' for two configurations.



Frequency sweep at node 'D' for two configurations.

- Harmonic load flow and frequency sweeps related to a node (in this case station D) are typical studies.
- *Example:* Two arbitrary configurations 1 & 2 – OHL changed with UGC:
  - ➢ Configuration 1 has introduced a higher voltage at node D as compared to configuration 2.
  - ➢ Resonances has moved towards lover frequencies.
- We can conclude that a voltage "amplification" has occurred moving from configuration 2 to 1.
- It could also be a change in harmonic propagation!

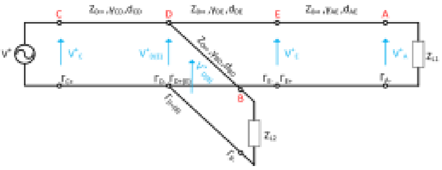
➡ ***It is inconclusive what has happened from this kind of studies***

- In this paper, we will refer to the distribution of harmonics as *harmonic propagation.*

3) Study cases

Case	Study type	Line configurations						Topology
		A-B	B-C	C-D	D-E	A-E	B-D	
1	Series OHL	OHL	OHL	OHL	OHL	OHL		Ring
2	Series UGC	OHL	OHL	OHL	OHL	UGC		Ring
3	Parallel OHL	OHL	OHL	OHL	OHL	OHL	OHL	Mesh
4	Parallel UGC	OHL	OHL	OHL	OHL	OHL	UGC	Mesh
5	Series and parallel UGC	OHL	OHL	OHL	OHL	UGC	UGC	Mesh
6	Topology change		OHL	OHL			UGC	Ring

- A total of six study cases has been set up:
  - ➢ Case 1 & 2: **Series connection** of OHL and UGC
  - ➢ Case 3 & 4: **Parallel connection**
  - ➢ Case 5: **Two UGC lines** (series and parallel)
  - ➢ Case 6: **Topology** changes
- Initially, a wave model has been set up, explaining the wave propagation phenomena analytically:



http://www.cigre.org

Study Committee C4

Power System Technical Performance

10563_2022

Analysis of Harmonic Propagation in Meshed Power Systems Using Standing Waves

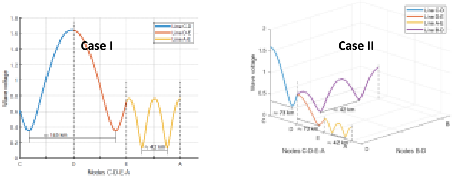
Method/Approach (cont.)

Wave model

- Harmonic source of 1 per unit @ 1000 Hz.
- Characteristic impedance and wavelength at 1000 Hz:

Type	Z_0	Wavelength [km] 1/4λ	1/2λ	3/4λ	1/1λ
OHL	299.5 – j0.55 Ω	73.15	146.31	219.46	292.62
UGC	53.28 – j0.10 Ω	21.42	42.84	64.27	85.69

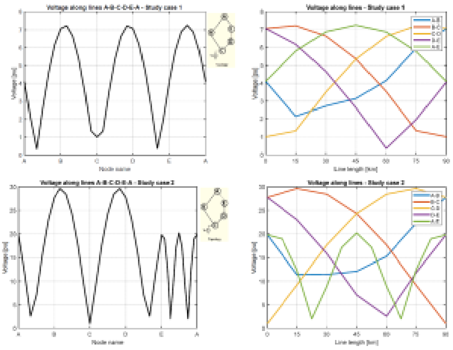
- Wave model setup for analytical comparison:
  - ➢ Case I: Three lines in series; C-D, D-E and E-A (OHL-OHL-UGC).
  - ➢ Case II: As Case I with a branch element D-B (UGC).
  - ➢ Same R/L/G/C parameters as for benchmark system.
- Analytical results:



- ➢ **Standing voltage wave patterns observed**
- ➢ **Specific profile for each line type (OHL or UGC)**
- ➢ **Terminal conditions determines voltage level**

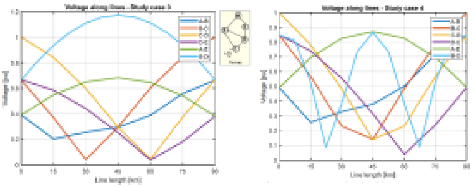
Experimental setup & test results

Study Case 1&2 – Series Connection



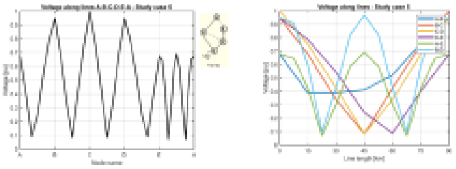
- Ring connection OHL and UGC (D-E).
- Voltage profiles according to theory of standing waves (Case I).
- **UGC leads to increased voltages** at nodes.
- Voltage profile changes only for affected line (A-E).

Study Case 3&4 – Parallel Connection



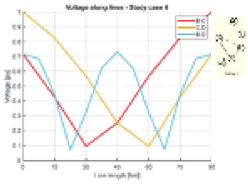
- Transverse connection B-D introduced both as OHL and UGC.
- **Transverse connection** leads to significantly **reduced voltages** at all nodes.
- Voltage profiles in upper ring B-A-E-D unaffected due to unchanged terminal conditions.
- Voltage profiles in lower ring B-C-D affected due to changed terminal conditions.
- Results according to theory of standing waves (Case II).

Study Case 5 – Multiple UGC



- Lines B-D and A-E are UGC.
- The results show that the (B-A-ED) and the (B-C-D-B) **line sections** can be **considered independently of each other's** topology as seen from the source.
- The voltage in the system is increased slightly as compared to case 3 and 4 (0.1 – 0.3 pu) but not as much as shown for case 2 (approx. 4 times).

Study Case 6 – Topology changes



- Upper ring B-A-E-D disconnected.
- Line B-D are UGC type.
- **Same voltage profile** along lines as for cases 3 and 4.

http://www.cigre.org

Study Committee C4

Power System Technical Performance

10563_2022

Analysis of Harmonic Propagation in Meshed Power Systems Using Standing Waves

Discussion

- Harmonic voltage can be interpreted as standing voltage waves along lines.
- Terminal conditions dictates the voltage profile.
- Voltage levels are determined by the path of propagation.
- Replacement of OHL with UGC leads to increased voltage at nodes.
- Parallel connections significantly decrease the voltage.

Key points:

Ring connection	For lines of same type as well as for different types, harmonic voltages can be considered as standing waves propagating along the lines. Conditions outside the ring do not affect the propagation in it.
Series UGC	An UGC in series with OHL leads to increased voltage magnitudes as compared to full-length OHL. The propagation of voltages on OHL remain unchanged in shape. Only the shape of the voltage wave on the UGC section changes.
Transverse connection in an existing meshed system	A new transverse connection in the meshed system leads to significantly decrease in harmonic voltage in the entire system regardless of the line type. The shape of the voltage waves changes due to changed terminal conditions where the transverse connection is established. The voltage profile along length of the remaining lines is unchanged.

Conclusion

- The methods presented here might be used as a tool for:
  - Determining the propagation of harmonics in a transmission system.
  - Determining the voltage propagating along one or more lines.
  - Determine the location of possible resonances in case a new substation must be inserted into a grid or if a line must be upgraded.

Future work

- Explanation of the physical correlation between harmonic propagation and amplification in a meshed system using standing waves.
- Development of a propagation model for:
  - Qualitatively describe the influence of system changes on the harmonic distribution,
  - Identify weak points in the system and
  - Identify the most appropriate locations of mitigating equipment.