Comprehensive Study of the Impact of Unbalanced Loading on Power Losses and Voltage Quality in Distribution Systems

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Introduction I

- Distribution system (DS): Last stage of transmission, supplies electrical energy.
- Fragility due to long distances, asymmetrical connections, and unsymmetrical loads.
- Issues affect operation, quality, and reliability of power.
- Requirements: Adequate power quality and acceptable power losses.
- Main problem: Unbalanced operation or unsymmetrical loading (UL).
- ULs cause power and voltage instability, risking continuity and economic of the power.
- Challenges: Lack of simulation platform and automated tools for UL.

This paper introduces a simulation platform for DS modeling and an assistant management algorithm to control unbalanced conditions using unified power controllers.

Agenda

2. Unified Power Controller
3. Methodology and Modeling
4. Case Study
5. Results
6. Conclusions

Symmetrical Compenants

- Symmetrical components analyze DS three-phase currents.
- Converts phases to positive, negative, and zero components.
- Control parameters: magnitude and angle of components.
- Uses transformer coefficients for control.

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} * \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = A * \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

Three-Wire System UPC

- Uses two transformers with controllable coefficients.
- Reactive element between transformers.
- Primary windings connected to the power line.
- Secondary windings connected in series with reactive element.

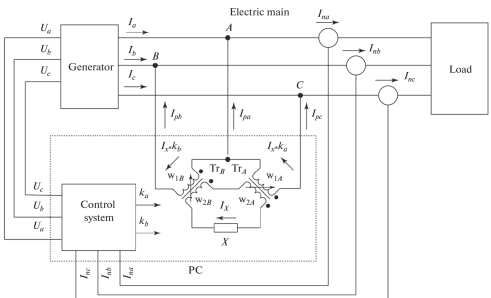


Figure: Three-phase UPC configuration for a three-wire system.

Four-Wire System UPC

- Two units: PCU and RPCU.
- PCU: Consistent transformer coefficient, reactive element.
- Thyristor for transformer coefficient control.
- RPCU: Three variable reactive elements.

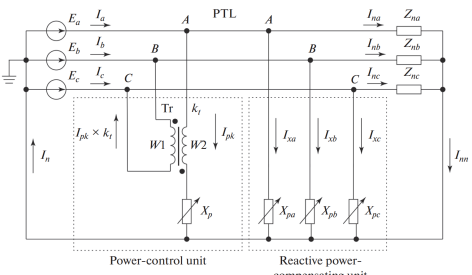
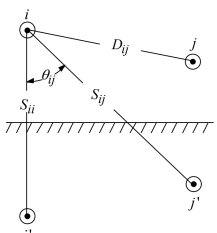


Figure: Four-phase DS Unified Power Controller configuration for a four-wire system.

Carson Equations I

- Carson Equations: Model DS Transmission Line (TL).
- Uses image theory to calculate impedance.
- Defines TL geometry, constructs matrix, applies equations.



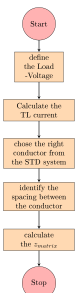


Figure: Distances and Angles for Impedance Calculation.

Carson Equations II

$$z_{ij} = 4G\omega P_{ij} + 2iG\omega\left(\ln\frac{s_{ij}}{D_{ij}} + 2Q_{ij}\right)$$

$$z_{ii} = (4G\omega P_{ii} + r_i) + 2iG\omega\left(\ln\frac{s_{ii}}{D_{ii}} + 2Q_{ii}\right)$$

$$P_{ij} = P'_{ij} + P''_{ij} + P'''_{ij} + P''''_{ij};$$

$$P'_{ij} = \frac{\pi}{8} - \frac{1}{3\cdot\sqrt{2}}\cdot k_{ij}\cdot\cos(\theta_{ij})$$

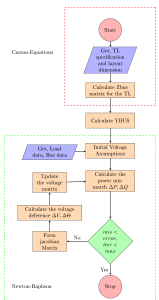
$$P''_{ij} = \frac{{k_{ij}}^2\cdot\cos(2\cdot\theta_{ij})}{16}\cdot\left(0.6728 + \ln\frac{2}{k_{ij}}\right)$$

$$p'''_{ij} = \frac{{k_{ij}}^2}{16}\cdot\theta_{ij}\cdot\sin(\theta_{ij})$$

$$P''''_{ij} = \frac{{k_{ij}}^3}{\sqrt{2}\cdot 45}\cdot\cos(3\cdot\theta_{ij}) - \frac{\pi\cdot{k_{ij}}^4}{1536}\cdot\cos(4\cdot\theta_{ij})$$

Newton-Raphson Method

- Basis for advanced studies: stability and reliability.
- Assess effectiveness of UPC in DS.
- Unbalance scenario: Change power on one phase, keep overall power constant.
- Main algorithms:
  1. Calculate power flow if phase A power changes from 0 to total.
  2. Calculate power losses for three phases and neutral.
  3. Calculate unbalancing coefficient.
  4. Calculate TL efficiency.



Assessing Unsymmetrical Loading

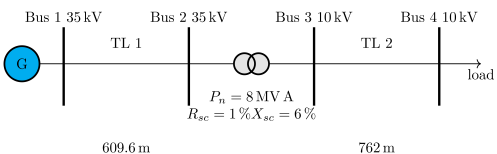
- Voltage unbalance: Total departure from nominal voltage.
- Unbalancing coefficient K_{Un}: Ratio between positive and negative symmetrical components.
- Must not exceed 1.5% per IEEE Std. 1159.3-2019.

$$U_r = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{\left(V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right)^2}$$

$$K_{Un}\% = \sqrt{\frac{1 - \sqrt{3 - 6U_r}}{1 + \sqrt{3 + 6U_r}}} * 100$$

Case Study

- System: Modified IEEE-4 bus system.
- Parameters updated for Russian systems.
- Transformer upscaled from 6 MV A to 8 MV A.
- Voltage level changed from 4.16 kV to 10 kV.
- Conducted cable sizing study for new parameters.



TL Impedance Matrix

- Maximum current: 227 A for 10 kV, 75 A for 35 kV.
- Chosen lines for currents shown in Table.
- Impedance matrices obtained using Carson equations.

Table: TI Impedance Matrix

	Units	TL 1	TL 2
GMR	(cm)	0.1267	0.18288
Resistance	($\Omega\,km^{-1}$)	5.12	1.164
Material	-	ACSR	ACSR
Stranding	-	6/1	6/1
Capacity	(A)	120	300

TL Impedance Matrices

Table: TI (1) Impedance Matrix ($\Omega\,\mathrm{km}^{-1}$)

	Phase A	Phase B	Phase C	Neutral line
Phase A	5.2452+2.199i	0.12537+1.0447i	0.12537+0.8775i	0.12554+0.95016i
Phase B	0.12537+1.0447i	5.2452+2.199i	0.12537+0.9492i	0.12554+1.0446i
Phase C	0.12537+0.8775i	0.12537+0.9492i	5.2452+2.199i	0.12554+0.98513i
Neutral line	0.12554+0.95016i	0.12554+1.0446i	0.12554+0.98513i	1.5747+2.7512i

Table: TI (2) Impedance Matrix ($\Omega\,\mathrm{km}^{-1}$)

	Phase A	Phase B	Phase C	Neutral line
Phase A	1.2894+2.1394i	0.12537+1.1574i	0.12537+0.99002i	0.12554+1.0246i
Phase B	0.12537+1.1574i	1.2894+2.1394i	0.12537+1.0618i	0.12554+1.0702i
Phase C	0.12537+0.99002i	0.12537+1.0618i	1.2894+2.1394i	0.12554+1.0446i
Neutral line	0.12554+1.0246i	0.12554+1.0702i	0.12554+1.0446i	1.5747+2.7512i

Load Data and Flow Results

Table: Load Data of the IEEE-4 Bus System

Phase	Active Power (kW)	Power Factor
A	2000	0.85 lag
B	2300	0.85 lag
C	3000	0.85 lag

Table: Load Flow Results

	Phase Magnitude (*pu*)			Phase Angle (*degree*)		
Busno	A	B	C	A	B	C
1	1	1	1	0	-120	120
2	0.9921	0.98951	0.9852	0.28742	-119.603	120.474
3	0.92253	0.90681	0.86473	-3.0213	-123.6319	114.9664
4	0.89864	0.86367	0.80046	-3.0631	-122.9769	113.9987

Results Overview

- Two groups of results: Reactive Power Compensation and Power Factor impact.
  - Reactive Power Compensation: Differentiates scenarios by reactive power.
  - Power Factor: Examines system response at different PF values (0.7, 0.8, 0.9, 1).

Scenario Description

1. Phase A active power change.
2. UPC compensates reactive power in Phase A.
3. UPC compensates reactive power in all phases.
4. UPC compensates TL reactive power for symmetrical DS.

Table: Loading Conditions for Each Scenario

	Active power (*MW*)			Reactive power (*Mvar*)		
Scenario no	A	B	C	A	B	C
1	2	2.3	3.5	1.7	1.95	2.55
2	2	2.3	3.5	0	1.95	2.55
3	2	2.3	3.5	0	0	0
4	2	2.3	3.5	0	0	0

Efficiency of Transmission Line

- Efficiency vs phase A power ratio ($P_A/P_{shortcircuit}$).
- Max efficiency at balanced power in all phases.
- Second scenario starts with lower efficiency due to reactive power removal in phase A.

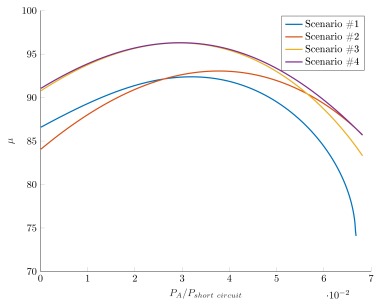


Figure: Efficiency of TL with Load Variation in Phase A.

Unbalancing Coefficient

- K_{Un} vs $P_A/P_{shortcircuit}$.
- Voltage quality impacted by single-phase reactive power compensation.
- Balancing point shifts right as phase A power increases.

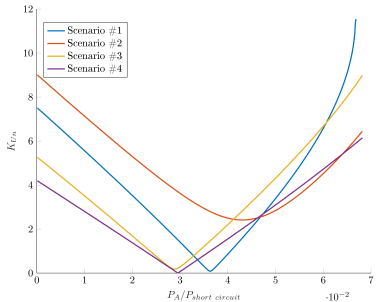


Figure: Unbalancing Coefficient vs Load Variation in Phase A.

Unbalancing Coefficient Analysis

- Decrease in unbalancing coefficient when negative sequence decreases.
- Scenario #2: Partial reactive power compensation reduces power losses but worsens voltage quality and stability.
- Best effect depends on reactive power compensation rather than balancing the system.

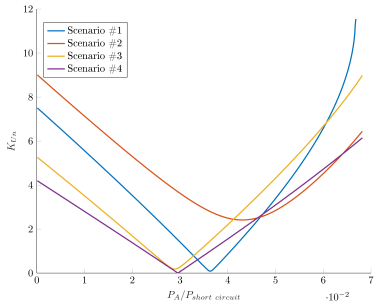


Figure: Unbalancing Coefficient vs Load Variation in Phase A.

Neutral Line Losses

- Neutral line losses vs $P_A/P_{shortcircuit}$.
- Losses increase with deviation from balanced point.
- Combined losses of three phases and neutral line shown in Figure.

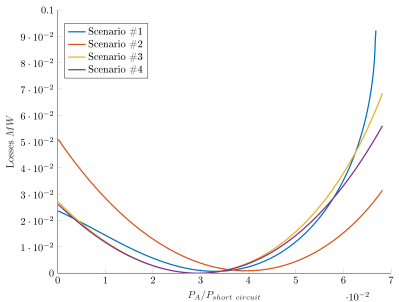


Figure: Neutral Line Losses vs Load Variation in Phase A.

Power Losses

- Three wire losses vs load variation in phase A.
- Red shaded area: Power losses reduction from 0.1 MW to 0.04 MW with reactive power compensation.
- Figure: Gray shaded area shows increased stability when reactive power is compensated.
- Unbalancing coefficient higher with reactive power due to increased phase currents Figure.

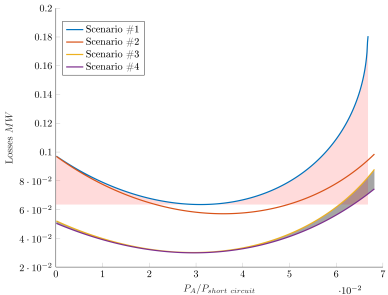


Figure: Four Wire Losses vs Load Variation in Phase A.

Power Losses Analysis

- Four wire losses vs load variation in phase A.
- Figure: UPC reduces power losses.
- Stability and voltage quality improve with reactive power compensation.
- Losses increase with unbalancing.

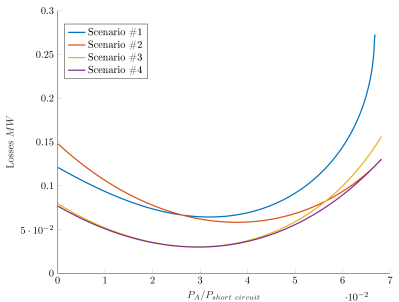


Figure: Four Wire Losses vs Load Variation in Phase A.

Power Factor Results

- Results for PF changes from 0.7 to 1.
- Losses reduced by enhancing PF.
- K_{Un} reduces with higher PF due to less negative component.

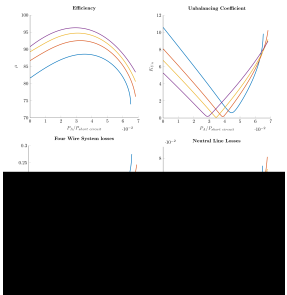


Figure: System Performance with PF Changes.

Conclusions

- Power electronics device introduced to solve asymmetric loads.
- Assessment includes:
  1. Efficiency of TL
  2. Unbalancing coefficient
  3. Power losses
- Russian compatible DS modeled using standard cable (35 kV-10 kV).
- Electrical model developed using Carson equation.
- Framework includes Newton-Raphson load flow, Carson equations, and IEEE standards.
- Results show performance improvements, addressing stability and economic issues.

Thank you!

Any questions.

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