Study Committee D1

Materials and Emerging Test Techniques

Paper D1-PS1-11110

Requirements, design principles and testing experience with composite voltages on a ±550 kV HVDC GIS voltage divider

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Motivation

- Worldwide development activities on HVDC GIS
- Type-tested product available up to U_r = ±550 kV DC
- Standardization prepared within CIGRE JWG D1/B3.57 with TB 842
  - additional thermo-electric tests to consider the special aspect of DC voltage in terms of electric field distribution of insulators, influenced by the accumulation of electrical charge carriers and the inhomogeneous temperature distribution
  - High importance: composite voltage testing (DC + impulse) after long DC pre-stress (reaching DC steady-state) with the maximum temperature gradient

Analysis of existing standards

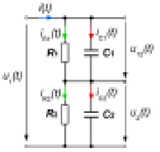
- Requirements for AC and DC withstand voltage tests are comparable
- Requirements for LI voltage tests are the same. SI voltage test acc. IEC 61869-15 only with a positive voltage, while acc. CIGRE TB 842 for both polarities
- Composite voltage tests not existing acc. IEC 61869-15. According to TB 842, composite voltage tests ensure appropriate insulation performance under transient overvoltages during operation

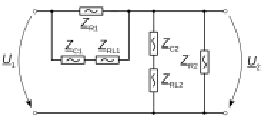
Example of applied type test values of a ±550 kV DC GIS incl. RC divider

Equipment U_r = U_m = ±550 kV		DC GIS	RC divider
Standard		CIGRE TB 842	IEC 61869-15
DC withstand voltage test	U_{DC} / kV	1.5xU_r = ±825 kV	
	t_{DC} / min	1	60
AC withstand voltage test	u_{AC} / kV	1.5xU_r/√2 = 583 kV	
	t_{AC} / min	1	
Impulse voltage test (not mandatory for DC GIS)	$Û_{LI}$ / kV	±1550	
	$Û_{SI}$ / kV	±1175	+1175
	# impulse	15 per polarity	
	I_n / A	0	0
Superimposed impulse voltage test (“Uncharged” dielectric interfaces)	U_{DC} / kV	±550	Not existing
	t_{DC} / h	2	
	$Û_{LI}$ / kV	±1550	
	$Û_{SI}$ / kV	±1175	
	# impulse	15 per quadrant	
	I_n / A	0	
Insulation system test (Superimposed impulse voltage test with “charged” dielectric interfaces)	U_{DC} / kV	±550	Not existing
	t_{DC} / h	> t_{90} = 120	
	$Û_{LI}$ / kV	±1550	
	$Û_{SI}$ / kV	±1175	
	# impulse	3 per quadrant	
	I_n / A	5000	

Design principles of RC dividers

- Equivalent circuit diagram (ECD) needs to include frequency dependency to cover system-dependent parasitic components
- Deriving impedance view of ECD allows identifying design criteria for improving the divider’s accuracy



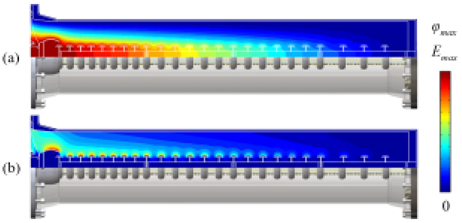


(Left) Simplified ECD. (Right) Advanced ECD in impedance view.

$$\underline{Z}_{R1} = R_1 \qquad \underline{Z}_{C1} = \frac{R_{pC1} - j\omega C_1 R_{pC1}^2}{1 + \omega^2 C_1^2 R_{pC1}^2} \qquad \underline{Z}_{RL1} = R_{sC1} + j\omega L_{C1}$$

Dependency of accuracy parameters ε_U , $\Delta\varphi$ on element variations

Element	Voltage error ε_U	Phase displacement $\Delta\varphi$
Positive trend ε_U ↑ $\Delta\phi$ ↑	C_1↑ C_2↓ R_1↓ R_2↑ L_{C1}↑ R_{pC1}↓ R_{sC2}↑	C_1↑ C_2↓ R_1↑ R_2↓ L_{C2}↑ R_{pC2}↓ R_{sC2}↑
Negative trend ε_U ↓ $\Delta\phi$ ↓	C_1↓ C_2↑ R_1↑ R_2↓ L_{C2}↑ R_{pC2}↓ R_{sC1}↑	C_1↓ C_2↑ R_1↓ R_2↑ L_{C1}↑ R_{pC1}↓ R_{sC1}↑



Principle of the internal GIS RC divider design – (a) Voltage potential distribution, (b) Corresponding electric field distribution

- Linear voltage distribution over the complete length of the RC divider
- Use of grading electrodes to move the electric field from internal divider insulation to gas space
- Capacitance and resistive components connected in parallel; use of *Allfilm* technology for C-elements
- Identical transformation ratios of the resistance part and the capacitance part leads to a flat frequency response curve
- Low-inductance capacitor design to prevent any transient overvoltage phenomena
- Divider internal insulation material must prevent charge accumulation, otherwise surface discharge can occur during impulse superposition (well-known POM-C cannot be used for DC applications)

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(continued)

Performance verification

Following IEC 61869-15 in combination with project-specific requirements, different accuracy measurements were performed to verify the characteristics of the GIS RC divider:

- AC accuracy at U_{pr} = 500 kV/√2 kV
- DC accuracy
  Note: At -250 kV a measurement uncertainty occurred due to the used measurement system of the test institute.
- Frequency response at 250 V, frequency bandwidth from 15 Hz up to 10 kHz
  - Voltage error shows an accuracy of ± 0.2 % within the total frequency range
  - Linear behaviour of the phase displacement indicates the impact on the length *l* of the transmission cable. Calculating the resulting Δ*φ* depending on the cable length l and the frequency *f*:

$$\Delta\varphi = \frac{360 \cdot 60 \cdot \sqrt{\varepsilon_r \mu_r} \cdot f \cdot l}{c_0}$$

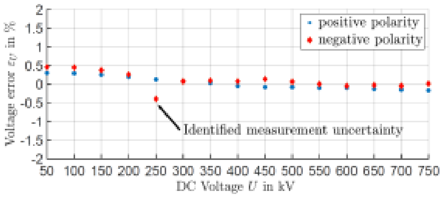
- Insulation system test acc. CIGRE TB 842 with composite voltage testing after long DC pre-stress of ±550 kV DC, exemplarily shown for unipolar & bipolar superposition with ±1550 kV LI
  - Impulse voltage, measured by the impulse divider of the impulse generator and by the GIS RC divider directly at the test object
  - The GIS RC divider is depicting the DC voltage and the superimposed lightning impulse
  - Fast polarity reversal during bipolar superposition requires insulating materials coping with accumulated charges
  - No runtime and amplitude calibration has been performed → slight shift between the two curves on the x- and y-axis can be seen and must be tolerated

Conclusions

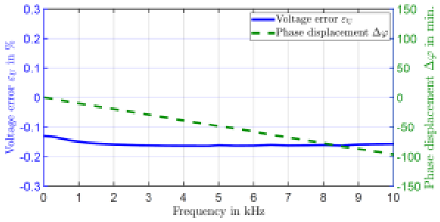
- Dimensioning GIS RC dividers acc. to IEC 61869-15 results in an insufficient design for the expected dielectric requirements during operation.
- Considering composite voltages as described by CIGRE JWG D1/B3.57 has a significant impact on electrical & mechanical design principles of RC dividers.
- Performance of the developed RC divider design has been proven by accuracy measurements, frequency response and composite voltage testing aiming to establish a high precision divider with a bandwidth of up to some ten kHz. Although accuracy in amplitude and waveshape is limited, the RC divider can be used to even measure DC+LI composite voltages.

AC accuracy performance results

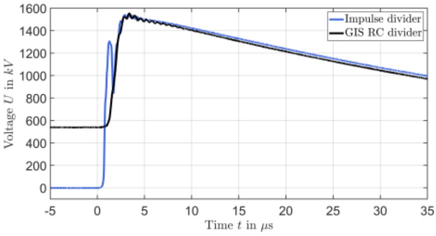
U_{pr} / %	± ε_U limit / %	± Δ*φ* limit / min	ε_U meas. / %	Δ*φ* meas. / min
80	≤ 1	10	0.36	-0.9
100	≤ 1	10	0.37	-0.9
120	≤ 1	10	0.39	-1.0



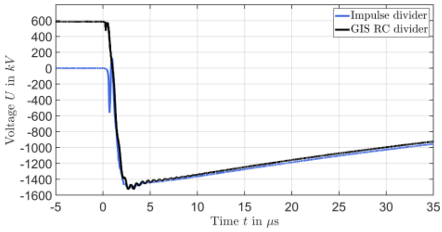
DC accuracy performance results



Frequency response measurement results



Composite voltage test of +550 kV DC and +1550 kV LI after more than 120 hours of DC pre-stress



Composite voltage test of +550 kV DC and -1550 kV LI after more than 120 hours of DC pre-stress