Estimation of Arc Voltage Based on High Energy Arching Faults Experiments

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1. Introduction

High Energy Arcing Faults (HEAF) are defined as faults that lead to the rapid release of electrical energy in the form of heat, vaporized metal, and mechanical force [1]. According to an OECD/NEA fire event report [2], there have been 48 HEAF events, accounting for approximately 10% of the total reported fire events. Since 2014, the USNRC and OECD/NEA have been conducting HEAF experiments [3~8] on low and medium voltage switchgears and bus ducts (BDs). Recently, a new research report, NUREG-2262 [1], was published focusing on the fire probabilistic safety assessment (PSA) of HEAF events.

The zone of influence (ZOI) presented in NUREG-2262 under the HEAF scenario is based on Fire Dynamic Simulator (FDS) [9] simulation results, which incorporate experimental data. The FDS simulation input factor with the greatest impact on the damage to target equipment is the arc energy, calculated using the following equation [1]:

(1) Arc energy=Arc power · Arc duration=
$I \cdot V_{(L\text{-}L)} \cdot \sqrt{3} \cdot$ Arc duration

where, I, arc current
$V_{(L\text{-}L)}$, line-to-line arc voltage

In NUREG-2262, a constant line-to-line voltage was used to calculate the arc energy of the HEAF-generating equipment. A voltage of 650V was used for medium voltage (MV) switchgear (SWGR) and BDs, while 375V was used for low voltage (LV) SWGR. The data for MV SWGR and BD were averaged using the values obtained from the CIGRE 602 [10] empirical formula due to the absence of experimental results. The line voltage for LV SWGR was set at the upper limit of values obtained from experiment data.

RIL 2023-01 [11], which estimates the arc voltage used in NUREG-2262, is based on the HEAF experimental report published in 2021. However, MV SWGR and BD HEAF test reports conducted after 2021 were not reviewed. Therefore, in this study, we estimated the arc voltage by reviewing the data from MV SWGR and BD HEAF experiments conducted thus far.

2. Methods and Results

2.1 Previous estimation results of arc voltages

This section outlines the process for estimating arc voltages as described in RIL 2023-01.

2.1.1 LV SWGR Arc Voltage

Arc voltage data from RIL 2021-17 [5] for LV (480V and 600V) SWGR HEAF experiments and RIL 2021-18 [6] for 1000V Open Box experiments were analyzed. The data from these two reports (RIL 2021-17 & 18) were evaluated to have a mean of 342V and a standard deviation of 54V. Assuming a t-distribution, the 95% confidence interval ranges between a maximum of 369V and a minimum of 315V. However, in RIL 2023-01, it appears that the mean and maximum were estimated using engineering judgment.

2.1.2 MV SWGR and Bus duct voltage

RIL 2021-10 [4] contains MV SWGR HEAF experiment results, but the arc voltage was not specified. The arc voltage mentioned in RIL 2021-10 refers to the generator voltage. Therefore, the following arc voltage formula from CIGRE 602 [10, 11] was used to estimate the arc voltage in RIL 2021-10:

(2) $$\frac{U_{arc}}{d} = 30\frac{V}{cm} + \frac{1}{2} I_{rms} \frac{V}{cm \cdot kA} \leq 40\frac{V}{cm}$$

where, U_{arc}, phase-to-phase (LL) arc voltage (volts)
d, distance between electrode centers (cm)
I_{rms}, the effective short circuit current (kA)

When applying the above equation to the open box test, a bias factor of 1.08 [11] was obtained by comparing the measured values with those predicted by the equation. As shown in Table I, the final arc voltage for MV SWGR and BD was obtained by considering the bias factor in the equation applied to MV SWGR.

Table I: CIGRE 602 estimates of arc voltage for 2018 tests

Test ID	I_{rms} (kA)	U_{gen}(V)	U_{arc} V)	U_{arc} (V) corrected
2-19	25.8	767	681	631
2-21	26.6	769	687	636
2-22	32	869	730	676
2-24	29.8	876	713	660

2.2 Estimation of MV SWGR and BD Arc Voltage from OECD HEAF Experiment Results

2.2.1 HEAF Experimental Data

The HEAF experimental data for MV SWGR and BD are summarized in the order of their published reports as follows:

(1) NEA/CSNI/R (2017) [3]: OECD Experiment, MV SWGR, System Voltage 6.9~10kV
(2) RIL 2021-10 [4]: US experiment, MV SWGR, System voltage 6.9 kV
(3) RIL 2021-18 [6]: US experiment, Open box, System voltage 6.9kV
(4) RIL 2023-07 [7]: OECD experiment, MV SWGR and Bus duct, system voltage 4.16~6.9kV
(5) RIL 2024-07 [8]: OECD experiment, MV SWGR and Bus duct, system voltage 4.16~6.9kV

After reviewing these reports, it was determined that reports (4) and (5) are suitable for estimating MV SWGR and BD arc voltage. The reasons for excluding reports (1) through (3) from the arc voltage estimation are as follows:

- NEA/CSNI/R (2017): As mentioned in Section 2.1.2, the CIGRE 602 equation was used due to the lack of experimental data. The arc voltage in this report is believed to represent the generator voltage.
- RIL 2021-10: As noted in Section 2.1.2, the arc voltages in this report refer to generator voltages.
- RIL 2021-18: The arc voltage described in this report is from the open box experiments and was t-tested against the arc voltage data in reports (4) and (5), determining that it was not the same type of data.

2.2.2 Estimation of MV SWGR and BD arc voltage using HEAF experiment results

Table II presents the HEAF experimental results for MV SWGR and BD from the RIL 2023-07 [7] and RIL 2024-07 [8] reports. The CIGRE arc voltage in Table II is the voltage predicted and corrected by Equation (2), following the approach used in RIL 2023-01 [11].

The arc voltage data in Table II were analyzed under the assumption of a t-distribution, with the results shown in Table III. Table III presents the arc voltage analysis results by report and equipment type. In Table III, 'All' represents the combined analysis of RIL 2023-07 and RIL 2024-07 data. Table IV provides the analysis results using the CIGRE 602 equation. Unlike Table III, the 95% confidence interval in Table IV does not significantly differ from the mean.

Based on the data from Tables III and IV, the average and 95% upper limit of MV SWGR and BD arc voltage are 730V and 760V, respectively. We recommend applying the average value of 730V to actual HEAF events, and using the 95% upper limit of 760V to determine the HEAF ZOI in the PSA. The 95% upper limit from Table IV was selected instead of that from Table III because the PSA is based on the best estimate, and the 95% upper limit in Table IV is closer to the mean.

3. Concluding Remarks

This paper reviews the results of HEAF experiments conducted by the United States and OECD/NEA, and estimates the arc voltage for MV SWGR and bus ducts. The arc voltage was estimated using data from HEAF experiments conducted after 2021. The average estimated arc voltage is 730V, with a 95% upper limit of 760V. If 760V is used to determine the HEAF ZOI for MV SWGR and bus ducts, it would be approximately 17% higher than the 650V currently used. In future work, we will perform FDS simulations using the estimated voltage to determine the HEAF ZOI.

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Table II: Arc voltages of RIL 2023-07 and 2024-07 HEAF Experiments

Report Number	Experiment ID	Voltage(kV)		Arc Current (kA)	Electrode/ Enclosure	Equipment	CIGRE Arc Voltage (V)-	
		System	Arc				Predicted	Corrected
RIL 2023-07	2-10	6.9	0.728	31.6	Cu/St	SWGR	841	779
RIL 2023-07	2-12	6.9	1.109	31.2	Cu/St	SWGR	837	775
RIL 2023-07	2-25	4.16	0.654	29.1	Cu/St	BD	818	757
RIL 2023-07	2-26	4.16	0.62	28.7	Cu/St	BD	814	754
RIL 2023-07	2-27	4.16	0.794	29.1	Cu/Al	BD	818	757
RIL 2023-07	2-28	4.16	0.839	28.4	Cu/Al	BD	812	751
RIL 2023-07	2-30*	4.16	0.942	28.4	Al/St	BD	812	751
RIL 2023-07	2-30b	4.16	0.711	28.8	Al/St	BD	815	755
RIL 2023-07	2-31	4.16	0.684	29.7	Al/Al	BD	823	762
RIL 2023-07	2-32	4.16	0.794	28.7	Al/Al	BD	814	754
RIL 2024-07	2-35	6.9	0.54	24.6	Cu.Al/St	SWGR	777	719
RIL 2024-07	2-36	6.9	0.49	24.4	Cu/St	SWGR	775	717
RIL 2024-07	2-37	6.9	0.63	24.1	Cu/St	SWGR	772	715
RIL 2024-07	2-38	6.9	0.64	24.2	Cu.Al/St	SWGR	773	716
RIL 2024-07	2-39	6.9	0.7	24.3	Cu/St	SWGR	774	717
RIL 2024-07	2-40	4.16	0.86	29.4	Cu/Al	BD	821	760
RIL 2024-07	2-41	4.16	0.85	29.3	Al/Al	BD	820	759

*2-30: Excluded from data analysis because the test was not successful

Table III: Estimation results of arc voltages based on arc voltage of each HEAF experiment in RIL 2023-07 and 2024-07

	RIL 2023	RIL 2024	All	SWGR only	BD only
Average	770.33	672.86	727.69	691.00	756.22
Standard deviation	145.53	142.09	147.87	202.36	90.51
95% confidence interval	111.86	131.41	78.79	187.15	69.57
95% Upper bound	882.20	804.27	806.48	878.15	825.79
95% Lower bound	658.47	541.44	648.89	503.85	686.65

Table IV: Estimation results of arc voltages based on the application of CIGRE 602 equation to HEAF experiment data in RIL 2023-07 and 2024-07

	RIL 2023	RIL 2024	All	SWGR only	BD only
Average	760.56	728.94	746.73	733.91	756.69
Standard deviation	9.80	20.91	22.10	29.41	3.47
95% confidence interval	7.53	19.34	11.78	27.20	2.67
95% Upper bound	768.09	748.27	758.50	761.12	759.36
95% Lower bound	753.03	709.60	734.95	706.71	754.02