

Data-Centric Federated Learning for Anomaly Detection in Smart Grids and other Industrial Control Systems

Tables with Experimental Paper Results

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This document presents, in the next pages, the tables with the detailed results from our experiments for both detection (binary) and classification (multiclass) scenarios. Columns describe measured time spent for detection and classification, percentage of minority class examples, and evaluation metrics. The improvement difference between the two approaches (baseline and proposed approach) is colored in green.

TABLE I
ATTACK DETECTION FOR BOT-IOT DATASET (BINARY)

Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC	
High-Volt.	1-25	Baseline	107.0	90.19 ± 13.13	8.46 ± 11.7	0.0 ± 0.0	1.35 ± 1.76	0.99 ± 0.02	0.99 ± 0.01	0.97 ± 0.06	0.98 ± 0.05	0.99 ± 0.01	
		Proposed method	89.0 -18.0	95.76 ± 6.54 +6%	3.48 ± 5.33 -5%	0.38 ± 1.15 +0%	0.38 ± 1.17 -1%	1.0 ± 0.0 +1%	1.0 ± 0.01 +1%	1.0 ± 0.0 +3%	1.0 ± 0.01 +2%	1.0 ± 0.0 +1%	
	1-50	Baseline	187.0	94.37 ± 10.18	4.32 ± 9.23	0.01 ± 0.08	1.31 ± 1.52	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.05	0.99 ± 0.03	1.0 ± 0.01	
		Proposed method	143.0 -44.0	97.71 ± 5.1 +3%	1.9 ± 4.16 -2%	0.19 ± 0.84 +0%	0.2 ± 0.85 -1%	1.0 ± 0.0 +1%	1.0 ± 0.01 +1%	1.0 ± 0.0 +1%	1.0 ± 0.01 +1%	1.0 ± 0.0 0%	
	1-75	Baseline	276.0	95.83 ± 8.58	2.88 ± 7.8	0.01 ± 0.07	1.29 ± 1.44	1.0 ± 0.01	0.99 ± 0.01	0.99 ± 0.04	0.99 ± 0.03	1.0 ± 0.01	
		Proposed method	209.0 -67.0	98.46 ± 4.27 +3%	1.28 ± 3.49 -2%	0.13 ± 0.69 +0%	0.13 ± 0.7 -1%	1.0 ± 0.0 0%	1.0 ± 0.01 +1%	1.0 ± 0.0 +1%	1.0 ± 0.0 +1%	1.0 ± 0.0 0%	
	1-100	Baseline	372.0	96.54 ± 7.57	2.17 ± 6.88	0.0 ± 0.06	1.29 ± 1.39	1.0 ± 0.01	1.0 ± 0.01	0.99 ± 0.03	0.99 ± 0.02	1.0 ± 0.01	
		Proposed method	273.0 -99.0	98.76 ± 3.74 +2%	1.04 ± 3.06 -1%	0.1 ± 0.6 +0%	0.1 ± 0.6 -1%	1.0 ± 0.0 0%	1.0 ± 0.01 0%	1.0 ± 0.0 +1%	1.0 ± 0.0 +1%	1.0 ± 0.0 0%	
	Distribution	1-25	Baseline	107.0	85.77 ± 18.42	12.33 ± 16.56	0.25 ± 1.1	1.65 ± 2.57	0.99 ± 0.01	0.99 ± 0.03	0.99 ± 0.03	0.98 ± 0.03	1.0 ± 0.02
			Proposed method	89.0 -18.0	91.27 ± 9.44 +6%	6.14 ± 7.48 -6%	1.16 ± 2.72 +1%	1.42 ± 2.23 +0%	0.99 ± 0.01 0%	0.99 ± 0.02 0%	0.99 ± 0.02 0%	0.99 ± 0.02 +1%	1.0 ± 0.01 0%
		1-50	Baseline	187.0	91.98 ± 14.47	6.44 ± 13.1	0.13 ± 0.79	1.45 ± 2.38	0.99 ± 0.01	0.99 ± 0.03	0.99 ± 0.02	0.99 ± 0.02	1.0 ± 0.02
			Proposed method	143.0 -44.0	91.9 ± 9.04 +0%	5.71 ± 7.42 -1%	1.66 ± 3.11 +2%	0.73 ± 1.74 -1%	1.0 ± 0.01 +1%	0.99 ± 0.02 0%	0.99 ± 0.02 0%	0.99 ± 0.01 0%	1.0 ± 0.0 0%
1-75		Baseline	276.0	94.2 ± 12.28	4.33 ± 11.1	0.09 ± 0.65	1.38 ± 2.31	1.0 ± 0.01	0.99 ± 0.03	0.99 ± 0.02	0.99 ± 0.02	1.0 ± 0.01	
		Proposed method	209.0 -67.0	91.91 ± 8.94 -2%	5.9 ± 7.67 +2%	1.71 ± 3.16 +2%	0.48 ± 1.46 -1%	1.0 ± 0.01 0%	0.99 ± 0.01 0%	1.0 ± 0.01 +1%	0.99 ± 0.01 0%	1.0 ± 0.0 0%	
1-100		Baseline	372.0	95.32 ± 10.89	3.26 ± 9.81	0.07 ± 0.56	1.36 ± 2.28	1.0 ± 0.01	0.99 ± 0.02	0.99 ± 0.02	0.99 ± 0.02	1.0 ± 0.01	
		Proposed method	273.0 -99.0	91.94 ± 8.93 -3%	5.82 ± 7.73 +3%	1.88 ± 3.26 +2%	0.36 ± 1.27 -1%	1.0 ± 0.01 0%	0.99 ± 0.01 0%	1.0 ± 0.01 +1%	1.0 ± 0.01 +1%	1.0 ± 0.0 0%	
Low-Volt.		1-25	Baseline	107.0	69.63 ± 32.71	25.02 ± 27.97	3.4 ± 7.53	1.95 ± 3.97	0.98 ± 0.03	0.97 ± 0.08	0.97 ± 0.09	0.96 ± 0.09	0.99 ± 0.07
			Proposed method	89.0 -18.0	82.12 ± 22.6 +12%	13.05 ± 19.8 -12%	2.36 ± 5.88 -1%	2.46 ± 4.08 +1%	0.99 ± 0.02 +1%	0.98 ± 0.03 +1%	0.98 ± 0.04 +1%	0.98 ± 0.04 +2%	0.99 ± 0.02 0%
		1-50	Baseline	187.0	74.63 ± 27.65	22.07 ± 23.94	1.7 ± 5.58	1.6 ± 3.67	0.99 ± 0.02	0.97 ± 0.07	0.98 ± 0.07	0.97 ± 0.07	0.99 ± 0.05
			Proposed method	143.0 -44.0	84.95 ± 18.86 +10%	9.31 ± 16.06 -13%	2.86 ± 6.43 +1%	2.87 ± 4.53 +1%	0.99 ± 0.02 0%	0.98 ± 0.03 +1%	0.99 ± 0.03 +1%	0.98 ± 0.03 +1%	0.99 ± 0.01 0%
	1-75	Baseline	276.0	76.27 ± 25.51	21.11 ± 22.33	1.13 ± 4.63	1.48 ± 3.56	0.99 ± 0.02	0.98 ± 0.06	0.98 ± 0.06	0.98 ± 0.06	0.99 ± 0.04	
		Proposed method	209.0 -67.0	85.66 ± 17.51 +9%	8.41 ± 14.5 -13%	2.95 ± 6.76 +2%	2.98 ± 4.79 +2%	0.99 ± 0.02 0%	0.99 ± 0.03 +1%	0.99 ± 0.03 +1%	0.99 ± 0.03 +1%	1.0 ± 0.01 +1%	
	1-100	Baseline	372.0	77.16 ± 24.4	20.56 ± 21.53	0.85 ± 4.04	1.42 ± 3.5	0.99 ± 0.02	0.98 ± 0.05	0.99 ± 0.05	0.98 ± 0.05	0.99 ± 0.04	
		Proposed method	273.0 -99.0	86.08 ± 16.59 +9%	8.03 ± 13.63 -13%	2.85 ± 6.59 +2%	3.04 ± 4.86 +2%	0.99 ± 0.01 0%	0.99 ± 0.02 +1%	0.99 ± 0.02 0%	0.99 ± 0.02 +1%	1.0 ± 0.01 +1%	

TABLE II
ATTACK DETECTION FOR IEC61850-SECURITY DATASET (BINARY)

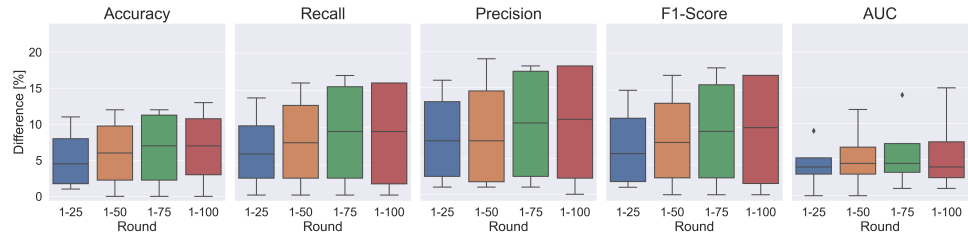
Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC	
High-Volt.	1-25	Baseline	169.0	15.31 ± 16.59	29.87 ± 20.27	17.47 ± 6.96	37.35 ± 30.96	0.61 ± 0.13	0.53 ± 0.19	0.54 ± 0.19	0.52 ± 0.2	0.67 ± 0.07	
		Proposed method	100.0 -69.0	14.95 ± 14.85 +0%	37.9 ± 19.57 +8%	18.94 ± 12.01 +1%	28.22 ± 22.39 -9%	0.63 ± 0.12 +2%	0.58 ± 0.16 +5%	0.6 ± 0.15 +6%	0.58 ± 0.16 +5%	0.72 ± 0.11 +5%	
	1-50	Baseline	315.0	18.36 ± 17.48	32.99 ± 17.54	16.05 ± 7.69	32.6 ± 28.02	0.67 ± 0.13	0.59 ± 0.19	0.6 ± 0.19	0.59 ± 0.19	0.74 ± 0.08	
		Proposed method	176.0 -139.0	19.21 ± 15.65 +1%	37.63 ± 15.7 +5%	16.46 ± 10.14 +0%	26.7 ± 20.65 -6%	0.7 ± 0.13 +3%	0.66 ± 0.17 +7%	0.68 ± 0.16 +8%	0.66 ± 0.17 +7%	0.78 ± 0.12 +4%	
	1-75	Baseline	480.0	19.24 ± 16.4	36.34 ± 16.38	14.73 ± 6.96	29.7 ± 26.09	0.71 ± 0.12	0.63 ± 0.18	0.65 ± 0.18	0.63 ± 0.18	0.77 ± 0.08	
		Proposed method	252.0 -228.0	20.37 ± 15.83 +1%	37.95 ± 14.11 +2%	15.94 ± 9.19 +1%	25.74 ± 19.78 -4%	0.74 ± 0.13 +3%	0.7 ± 0.16 +7%	0.72 ± 0.15 +7%	0.7 ± 0.16 +7%	0.82 ± 0.11 +5%	
	1-100	Baseline	692.0	18.4 ± 15.01	39.58 ± 17.02	14.11 ± 6.65	27.9 ± 24.9	0.73 ± 0.11	0.66 ± 0.17	0.68 ± 0.17	0.66 ± 0.17	0.79 ± 0.08	
		Proposed method	337.0 -355.0	20.65 ± 15.36 +2%	39.47 ± 13.49 +0%	15.24 ± 8.57 +1%	24.64 ± 19.17 -3%	0.76 ± 0.12 +3%	0.72 ± 0.15 +6%	0.74 ± 0.14 +6%	0.72 ± 0.15 +6%	0.83 ± 0.1 +4%	
	Distribution	1-25	Baseline	169.0	14.93 ± 16.21	30.54 ± 20.72	15.2 ± 7.29	39.33 ± 32.61	0.57 ± 0.13	0.49 ± 0.18	0.5 ± 0.19	0.48 ± 0.18	0.64 ± 0.06
			Proposed method	100.0 -69.0	15.41 ± 14.9 +0%	39.94 ± 19.37 +9%	18.31 ± 14.02 +3%	26.34 ± 20.46 -13%	0.62 ± 0.14 +5%	0.58 ± 0.17 +9%	0.59 ± 0.17 +9%	0.57 ± 0.17 +8%	0.72 ± 0.1 +8%
		1-50	Baseline	315.0	16.16 ± 17.03	30.89 ± 20.71	16.76 ± 11.61	36.19 ± 31.18	0.61 ± 0.12	0.54 ± 0.18	0.55 ± 0.18	0.53 ± 0.18	0.69 ± 0.07
			Proposed method	176.0 -139.0	17.96 ± 15.44 +2%	38.78 ± 17.41 +8%	17.21 ± 11.87 +0%	26.05 ± 20.58 -10%	0.67 ± 0.13 +6%	0.63 ± 0.16 +9%	0.65 ± 0.16 +10%	0.62 ± 0.16 +9%	0.76 ± 0.1 +7%
1-75		Baseline	480.0	15.75 ± 16.47	32.52 ± 21.27	17.5 ± 11.9	34.23 ± 30.32	0.64 ± 0.11	0.57 ± 0.16	0.58 ± 0.16	0.56 ± 0.17	0.71 ± 0.07	
		Proposed method	252.0 -228.0	17.92 ± 15.95 +2%	40.1 ± 16.15 +8%	16.73 ± 10.89 -1%	25.25 ± 20.25 -9%	0.7 ± 0.12 +6%	0.66 ± 0.15 +9%	0.68 ± 0.15 +10%	0.66 ± 0.15 +10%	0.79 ± 0.1 +8%	
1-100		Baseline	692.0	14.37 ± 15.36	35.01 ± 22.44	17.74 ± 11.59	32.88 ± 29.63	0.66 ± 0.1	0.59 ± 0.16	0.61 ± 0.15	0.59 ± 0.16	0.72 ± 0.07	
		Proposed method	337.0 -355.0	17.71 ± 15.84 +3%	41.54 ± 15.64 +7%	16.33 ± 10.61 -1%	24.43 ± 19.87 -8%	0.72 ± 0.11 +6%	0.68 ± 0.14 +9%	0.71 ± 0.14 +10%	0.68 ± 0.15 +9%	0.8 ± 0.1 +8%	
Low-Volt.		1-25	Baseline	169.0	12.85 ± 15.02	33.24 ± 24.71	14.55 ± 8.84	39.36 ± 33.59	0.51 ± 0.13	0.45 ± 0.17	0.43 ± 0.19	0.43 ± 0.18	0.59 ± 0.08
			Proposed method	100.0 -69.0	13.51 ± 14.62 +1%	39.83 ± 23.7 +7%	20.0 ± 15.42 +5%	26.64 ± 24.4 -13%	0.58 ± 0.17 +7%	0.54 ± 0.19 +9%	0.55 ± 0.2 +12%	0.53 ± 0.2 +10%	0.68 ± 0.13 +9%
		1-50	Baseline	315.0	13.95 ± 15.24	31.82 ± 24.53	16.44 ± 11.85	37.8 ± 32.85	0.51 ± 0.11	0.43 ± 0.17	0.43 ± 0.18	0.42 ± 0.17	0.58 ± 0.07
			Proposed method	176.0 -139.0	16.04 ± 15.68 +2%	37.71 ± 21.49 +6%	18.7 ± 14.02 +2%	27.55 ± 23.92 -10%	0.6 ± 0.16 +9%	0.55 ± 0.2 +12%	0.56 ± 0.2 +13%	0.54 ± 0.2 +12%	0.7 ± 0.13 +12%
	1-75	Baseline	480.0	13.39 ± 14.5	32.83 ± 24.88	17.72 ± 11.89	36.06 ± 31.91	0.5 ± 0.1	0.42 ± 0.16	0.42 ± 0.16	0.41 ± 0.16	0.57 ± 0.07	
		Proposed method	252.0 -228.0	15.86 ± 15.36 +2%	38.02 ± 21.0 +5%	18.21 ± 13.14 +0%	27.9 ± 24.22 -8%	0.62 ± 0.16 +12%	0.57 ± 0.19 +15%	0.59 ± 0.2 +17%	0.56 ± 0.19 +15%	0.71 ± 0.13 +14%	
	1-100	Baseline	692.0	12.1 ± 13.42	34.39 ± 26.49	18.25 ± 11.54	35.26 ± 31.65	0.49 ± 0.09	0.41 ± 0.15	0.41 ± 0.16	0.4 ± 0.15	0.56 ± 0.07	
		Proposed method	337.0 -355.0	15.59 ± 14.73 +3%	39.29 ± 21.25 +5%	17.62 ± 12.66 -1%	27.5 ± 23.96 -8%	0.62 ± 0.15 +13%	0.57 ± 0.18 +16%	0.59 ± 0.19 +18%	0.57 ± 0.18 +17%	0.71 ± 0.14 +15%	

TABLE III
ATTACK DETECTION FOR NSL-KDD DATASET (BINARY)

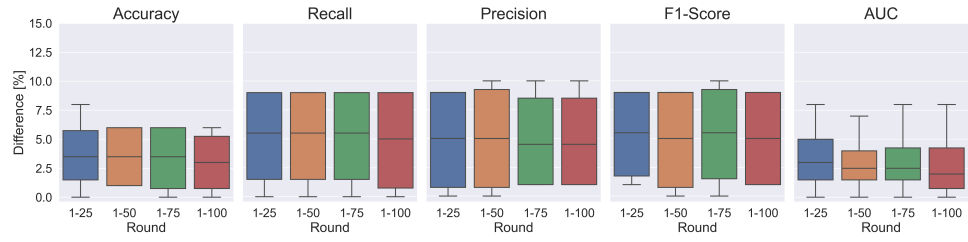
Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC
High-Volt.	1-25	Baseline	150.0	83.43 ± 1.82	10.13 ± 3.2	1.73 ± 1.12	4.71 ± 1.41	0.94 ± 0.05	0.93 ± 0.05	0.94 ± 0.05	0.94 ± 0.05	0.93 ± 0.05
		Proposed method	286.0	90.29 ± 3.39	5.48 ± 2.47	1.61 ± 1.13	2.62 ± 1.05	0.96 ± 0.03	0.95 ± 0.03	0.96 ± 0.04	0.95 ± 0.03	0.95 ± 0.03
			136.0	+7%	-5%	+0%	-2%	+2%	+2%	+2%	+1%	+2%
	1-50	Baseline	298.0	84.55 ± 3.13	10.66 ± 3.11	1.37 ± 0.92	3.42 ± 1.66	0.96 ± 0.04	0.96 ± 0.05	0.96 ± 0.04	0.96 ± 0.04	0.96 ± 0.05
		Proposed method	541.0	91.94 ± 2.95	5.18 ± 1.87	1.22 ± 0.93	1.66 ± 1.23	0.97 ± 0.03	0.97 ± 0.03	0.97 ± 0.03	0.97 ± 0.03	0.97 ± 0.03
			243.0	+7%	-5%	+0%	-2%	+1%	+1%	+1%	+1%	+1%
	1-75	Baseline	468.0	86.42 ± 3.7	9.88 ± 2.82	1.0 ± 0.92	2.7 ± 1.7	0.97 ± 0.03	0.97 ± 0.04	0.97 ± 0.04	0.97 ± 0.04	0.97 ± 0.04
		Proposed method	843.0	92.86 ± 2.77	4.97 ± 1.63	0.93 ± 0.86	1.23 ± 1.18	0.98 ± 0.03	0.98 ± 0.03	0.98 ± 0.03	0.98 ± 0.03	0.98 ± 0.03
			375.0	+6%	-5%	+0%	-1%	+1%	+1%	+1%	+1%	+1%
	1-100	Baseline	676.0	87.43 ± 3.67	9.56 ± 2.51	0.79 ± 0.88	2.21 ± 1.7	0.98 ± 0.03	0.97 ± 0.04	0.98 ± 0.03	0.98 ± 0.03	0.97 ± 0.04
		Proposed method	1210.0	93.24 ± 2.49	5.04 ± 1.43	0.75 ± 0.81	0.97 ± 1.12	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02
			534.0	+6%	-5%	+0%	-1%	0%	+1%	0%	0%	+1%
Distribution	1-25	Baseline	150.0	83.15 ± 3.64	5.75 ± 1.4	5.08 ± 2.97	6.02 ± 2.38	0.95 ± 0.03	0.94 ± 0.04	0.95 ± 0.03	0.94 ± 0.03	0.94 ± 0.04
		Proposed method	286.0	86.6 ± 4.24	7.89 ± 3.61	2.08 ± 1.5	3.43 ± 1.28	0.97 ± 0.02	0.96 ± 0.03	0.96 ± 0.02	0.96 ± 0.03	0.96 ± 0.03
			136.0	+3%	+2%	-3%	-3%	+2%	+2%	+1%	+2%	+2%
	1-50	Baseline	298.0	82.43 ± 3.08	6.82 ± 2.27	6.42 ± 3.13	4.34 ± 2.45	0.96 ± 0.03	0.95 ± 0.03	0.96 ± 0.03	0.96 ± 0.03	0.95 ± 0.03
		Proposed method	541.0	88.26 ± 3.85	7.4 ± 3.02	2.08 ± 1.21	2.26 ± 1.53	0.97 ± 0.02	0.97 ± 0.02	0.97 ± 0.02	0.97 ± 0.02	0.97 ± 0.02
			243.0	+6%	+1%	-4%	-2%	+1%	+2%	+1%	+1%	+2%
	1-75	Baseline	468.0	83.75 ± 3.23	7.44 ± 2.2	5.42 ± 2.94	3.4 ± 2.41	0.97 ± 0.03	0.96 ± 0.03	0.97 ± 0.02	0.96 ± 0.03	0.96 ± 0.03
		Proposed method	843.0	89.43 ± 3.62	6.78 ± 2.71	2.1 ± 1.02	1.69 ± 1.49	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02
			375.0	+6%	-1%	-3%	-2%	+1%	+2%	+1%	+2%	+2%
	1-100	Baseline	676.0	85.14 ± 3.72	7.01 ± 2.11	5.02 ± 2.64	2.83 ± 2.3	0.97 ± 0.02	0.97 ± 0.03	0.97 ± 0.02	0.97 ± 0.03	0.97 ± 0.03
		Proposed method	1210.0	90.22 ± 3.42	6.47 ± 2.41	1.97 ± 0.92	1.34 ± 1.43	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02	0.98 ± 0.02
			534.0	+5%	-1%	-3%	-1%	+1%	+1%	+1%	+1%	+1%
Low-Volt.	1-25	Baseline	150.0	77.93 ± 4.54	7.62 ± 3.85	5.6 ± 3.16	8.84 ± 2.15	0.92 ± 0.05	0.9 ± 0.06	0.92 ± 0.05	0.91 ± 0.06	0.9 ± 0.06
		Proposed method	286.0	82.19 ± 5.91	9.25 ± 4.23	4.16 ± 2.65	4.41 ± 1.94	0.94 ± 0.05	0.94 ± 0.05	0.95 ± 0.04	0.94 ± 0.05	0.94 ± 0.05
			136.0	+4%	+2%	-1%	-4%	+2%	+4%	+3%	+3%	+4%
	1-50	Baseline	298.0	77.2 ± 3.72	9.7 ± 3.76	5.07 ± 2.68	8.02 ± 2.16	0.92 ± 0.04	0.91 ± 0.05	0.93 ± 0.04	0.91 ± 0.05	0.91 ± 0.05
		Proposed method	541.0	82.96 ± 5.29	10.29 ± 3.94	3.08 ± 2.33	3.66 ± 1.72	0.95 ± 0.04	0.95 ± 0.04	0.95 ± 0.04	0.95 ± 0.04	0.95 ± 0.04
			243.0	+6%	+1%	-2%	-4%	+3%	+4%	+2%	+4%	+4%
	1-75	Baseline	468.0	77.97 ± 3.37	11.16 ± 3.8	4.1 ± 2.65	6.77 ± 2.53	0.93 ± 0.04	0.92 ± 0.05	0.93 ± 0.04	0.92 ± 0.04	0.92 ± 0.05
		Proposed method	843.0	85.02 ± 5.34	9.46 ± 3.55	2.46 ± 2.13	3.06 ± 1.69	0.96 ± 0.04	0.96 ± 0.04	0.96 ± 0.03	0.96 ± 0.04	0.96 ± 0.04
			375.0	+7%	-2%	-2%	-4%	+3%	+4%	+3%	+4%	+4%
	1-100	Baseline	676.0	80.18 ± 4.97	10.39 ± 3.77	3.5 ± 2.55	5.93 ± 2.64	0.93 ± 0.04	0.93 ± 0.04	0.94 ± 0.04	0.93 ± 0.04	0.93 ± 0.04
		Proposed method	1210.0	86.8 ± 5.58	8.52 ± 3.5	2.08 ± 1.97	2.61 ± 1.66	0.97 ± 0.03	0.96 ± 0.04	0.97 ± 0.03	0.96 ± 0.04	0.96 ± 0.04
			534.0	+7%	-2%	-1%	-3%	+4%	+3%	+3%	+3%	+3%

TABLE IV
ATTACK DETECTION FOR UNSW-NB15 DATASET (BINARY)

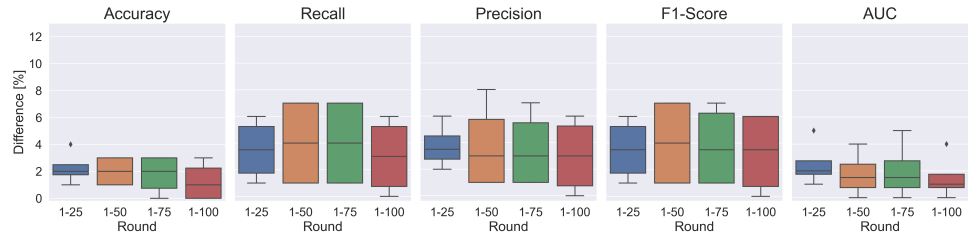
Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC
High-Volt.	1-25	Baseline	113.0	33.72 ± 33.51	36.78 ± 13.89	15.69 ± 13.59	13.81 ± 10.51	0.8 ± 0.11	0.74 ± 0.17	0.77 ± 0.14	0.74 ± 0.17	0.91 ± 0.03
		Proposed method	96.0	44.03 ± 27.85	40.09 ± 16.37	7.71 ± 5.92	8.18 ± 7.25	0.84 ± 0.12	0.8 ± 0.16	0.81 ± 0.15	0.79 ± 0.16	0.93 ± 0.05
			-17.0	+10%	+3%	-8%	-6%	+4%	+6%	+4%	+5%	+2%
	1-50	Baseline	215.0	35.98 ± 34.62	31.95 ± 11.82	15.38 ± 13.97	16.69 ± 14.7	0.84 ± 0.1	0.77 ± 0.16	0.8 ± 0.13	0.77 ± 0.15	0.93 ± 0.03
		Proposed method	187.0	44.74 ± 29.9	35.91 ± 15.06	9.2 ± 8.93	10.15 ± 9.36	0.87 ± 0.1	0.84 ± 0.13	0.85 ± 0.12	0.84 ± 0.13	0.95 ± 0.04
			-28.0	+9%	+4%	-6%	-7%	+3%	+7%	+5%	+7%	+2%
	1-75	Baseline	324.0	40.02 ± 34.15	31.34 ± 11.65	12.85 ± 12.92	15.79 ± 14.36	0.86 ± 0.09	0.79 ± 0.15	0.82 ± 0.13	0.79 ± 0.15	0.94 ± 0.03
		Proposed method	284.0	46.4 ± 30.53	33.42 ± 14.78	9.28 ± 9.06	10.89 ± 10.02	0.89 ± 0.09	0.86 ± 0.12	0.87 ± 0.11	0.85 ± 0.12	0.96 ± 0.04
			-40.0	+6%	+2%	-4%	-5%	+3%	+7%	+5%	+6%	+2%
	1-100	Baseline	457.0	41.59 ± 35.47	29.42 ± 11.95	12.24 ± 12.75	16.75 ± 16.1	0.88 ± 0.09	0.81 ± 0.15	0.83 ± 0.12	0.81 ± 0.14	0.95 ± 0.03
		Proposed method	386.0	50.04 ± 29.99	32.24 ± 15.54	7.82 ± 8.58	9.9 ± 9.41	0.9 ± 0.08	0.86 ± 0.12	0.88 ± 0.11	0.87 ± 0.12	0.96 ± 0.03
			-71.0	+8%	+3%	-4%	-7%	+2%	+5%	+5%	+6%	+1%
Distribution	1-25	Baseline	113.0	30.82 ± 29.03	35.54 ± 5.77	18.91 ± 15.07	14.74 ± 11.34	0.77 ± 0.11	0.71 ± 0.17	0.73 ± 0.16	0.71 ± 0.17	0.89 ± 0.04
		Proposed method	96.0	40.22 ± 28.92	41.96 ± 18.31	9.19 ± 8.25	8.64 ± 9.1	0.85 ± 0.09	0.8 ± 0.13	0.82 ± 0.13	0.8 ± 0.14	0.93 ± 0.05
			-17.0	+9%	+6%	-10%	-6%	+8%	+9%	+9%	+9%	+4%
	1-50	Baseline	215.0	31.78 ± 31.05	33.68 ± 8.09	14.02 ± 13.48	20.52 ± 20.45	0.81 ± 0.1	0.74 ± 0.16	0.76 ± 0.15	0.74 ± 0.17	0.91 ± 0.04
		Proposed method	187.0	39.89 ± 29.02	37.59 ± 16.29	11.51 ± 10.59	11.02 ± 12.15	0.87 ± 0.08	0.83 ± 0.12	0.85 ± 0.11	0.83 ± 0.12	0.94 ± 0.04
			-28.0	+8%	+4%	-3%	-10%	+6%	+9%	+9%	+9%	+3%
	1-75	Baseline	324.0	32.73 ± 32.35	37.43 ± 14.67	11.78 ± 11.91	18.06 ± 19.16	0.83 ± 0.1	0.76 ± 0.16	0.79 ± 0.14	0.76 ± 0.16	0.92 ± 0.04
		Proposed method	284.0	41.03 ± 29.46	35.66 ± 15.53	11.4 ± 10.11	11.91 ± 12.48	0.89 ± 0.08	0.85 ± 0.12	0.87 ± 0.11	0.85 ± 0.12	0.95 ± 0.04
			-40.0	+8%	-2%	+0%	-6%	+6%	+9%	+8%	+9%	+3%
	1-100	Baseline	457.0	33.92 ± 33.78	34.33 ± 16.74	11.63 ± 11.98	20.13 ± 22.48	0.85 ± 0.09	0.77 ± 0.16	0.8 ± 0.14	0.77 ± 0.16	0.93 ± 0.04
		Proposed method	386.0	42.09 ± 30.02	35.97 ± 16.41	10.77 ± 9.87	11.17 ± 11.84	0.9 ± 0.07	0.86 ± 0.12	0.88 ± 0.11	0.86 ± 0.12	0.96 ± 0.04
			-71.0	+8%	+2%	-1%	-9%	+5%	+9%	+8%	+9%	+3%
Low-Volt.	1-25	Baseline	113.0	29.1 ± 29.62	24.61 ± 13.63	20.28 ± 18.29	26.0 ± 23.15	0.71 ± 0.16	0.65 ± 0.2	0.64 ± 0.22	0.63 ± 0.22	0.86 ± 0.06
		Proposed method	96.0	38.42 ± 30.31	39.2 ± 19.14	11.4 ± 14.28	10.98 ± 10.54	0.82 ± 0.11	0.79 ± 0.14	0.8 ± 0.13	0.78 ± 0.15	0.9 ± 0.08
			-17.0	+9%	+15%	-9%	-15%	+11%	+14%	+16%	+15%	+4%
	1-50	Baseline	215.0	29.67 ± 29.99	27.57 ± 13.43	18.4 ± 17.17	24.37 ± 23.07	0.72 ± 0.14	0.65 ± 0.2	0.64 ± 0.21	0.63 ± 0.21	0.86 ± 0.06
		Proposed method	187.0	37.52 ± 29.56	38.28 ± 17.45	11.43 ± 13.49	12.77 ± 12.36	0.84 ± 0.09	0.81 ± 0.13	0.83 ± 0.12	0.8 ± 0.13	0.91 ± 0.07
			-28.0	+8%	+11%	-7%	-12%	+12%	+16%	+19%	+17%	+5%
	1-75	Baseline	324.0	30.56 ± 30.84	31.14 ± 16.42	15.55 ± 16.82	22.75 ± 22.84	0.74 ± 0.13	0.65 ± 0.21	0.65 ± 0.22	0.63 ± 0.22	0.87 ± 0.05
		Proposed method	284.0	37.62 ± 29.9	37.27 ± 16.67	11.11 ± 13.19	14.0 ± 13.39	0.85 ± 0.09	0.82 ± 0.13	0.83 ± 0.12	0.81 ± 0.14	0.92 ± 0.07
			-40.0	+7%	+6%	-4%	-9%	+11%	+17%	+18%	+18%	+5%
	1-100	Baseline	457.0	31.74 ± 32.1	29.15 ± 16.52	14.84 ± 16.86	24.27 ± 25.54	0.75 ± 0.12	0.65 ± 0.22	0.65 ± 0.22	0.64 ± 0.22	0.87 ± 0.05
		Proposed method	386.0	37.88 ± 30.97	37.29 ± 16.88	11.06 ± 13.32	13.77 ± 13.15	0.85 ± 0.09	0.81 ± 0.14	0.83 ± 0.13	0.81 ± 0.14	0.92 ± 0.06
			-71.0	+6%	+8%	-4%	-10%	+10%	+16%	+18%	+17%	+5%



(a) Low-Voltage (lower layer)



(b) Distribution (mid layer)



(c) High-Voltage (top layer)

Fig. 1. Gain between the baseline and proposed method for each substation (binary scenario) – different colors represent different time blocks

TABLE V
ATTACK CLASSIFICATION FOR BOT-IoT DATASET (MULTICLASS)

Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC
High-Volt.	1-25	Baseline	91.0	81.5 ± 13.88	15.8 ± 12.86	0.0 ± 0.0	2.7 ± 1.6	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
		Proposed method	89.0	91.51 ± 7.06	6.96 ± 5.73	0.76 ± 1.55	0.77 ± 1.57	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
			-2.0	+10%	-9%	+1%	-2%	0%	0%	0%	0%	0%
	1-50	Baseline	174.0	89.5 ± 12.64	7.9 ± 12.03	0.0 ± 0.0	2.6 ± 1.12	1.0 ± 0.0	0.99 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
		Proposed method	143.0	95.43 ± 6.47	3.79 ± 5.27	0.39 ± 1.16	0.39 ± 1.18	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
			-31.0	+6%	-4%	+0%	-2%	0%	+1%	0%	0%	0%
	1-75	Baseline	253.0	92.17 ± 10.96	5.27 ± 10.48	0.0 ± 0.0	2.57 ± 0.92	1.0 ± 0.0	0.99 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
		Proposed method	209.0	96.98 ± 5.68	2.51 ± 4.64	0.26 ± 0.96	0.26 ± 0.97	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
			-44.0	+5%	-3%	+0%	-2%	0%	+1%	0%	0%	0%
	1-100	Baseline	337.0	93.5 ± 9.76	3.95 ± 9.35	0.0 ± 0.0	2.55 ± 0.79	1.0 ± 0.0	0.99 ± 0.01	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0
		Proposed method	273.0	97.61 ± 5.04	2.01 ± 4.12	0.19 ± 0.84	0.19 ± 0.85	1.0 ± 0.0	1.0 ± 0.01	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0
			-64.0	+4%	-2%	+0%	-2%	0%	+1%	0%	0%	0%
Distribution	1-25	Baseline	91.0	72.4 ± 17.88	23.8 ± 16.86	0.5 ± 1.52	3.3 ± 2.79	0.99 ± 0.01	0.98 ± 0.03	0.99 ± 0.02	0.98 ± 0.02	1.0 ± 0.0
		Proposed method	89.0	82.54 ± 4.94	12.29 ± 5.99	2.33 ± 3.48	2.84 ± 2.43	1.0 ± 0.01	0.99 ± 0.02	1.0 ± 0.01	0.99 ± 0.01	1.0 ± 0.0
			-2.0	+10%	-12%	+2%	+0%	+1%	+1%	+1%	+1%	0%
	1-50	Baseline	174.0	84.95 ± 17.9	11.9 ± 16.84	0.25 ± 1.1	2.9 ± 2.68	0.99 ± 0.01	0.98 ± 0.03	0.99 ± 0.01	0.99 ± 0.02	1.0 ± 0.0
		Proposed method	143.0	83.85 ± 5.75	11.38 ± 6.75	3.32 ± 3.73	1.45 ± 2.24	1.0 ± 0.01	0.99 ± 0.02	1.0 ± 0.01	0.99 ± 0.01	1.0 ± 0.0
			-31.0	-1%	-1%	+3%	-1%	+1%	+1%	+1%	0%	0%
	1-75	Baseline	253.0	89.13 ± 15.82	7.93 ± 14.84	0.17 ± 0.9	2.77 ± 2.63	0.99 ± 0.01	0.98 ± 0.03	0.99 ± 0.02	0.99 ± 0.03	1.0 ± 0.0
		Proposed method	209.0	84.12 ± 6.16	11.49 ± 7.4	3.43 ± 3.76	0.96 ± 1.95	1.0 ± 0.01	0.99 ± 0.02	1.0 ± 0.0	0.99 ± 0.01	1.0 ± 0.0
			-44.0	-5%	+4%	+3%	-2%	+1%	+1%	0%	0%	0%
	1-100	Baseline	337.0	91.22 ± 14.22	5.95 ± 13.29	0.12 ± 0.78	2.7 ± 2.6	1.0 ± 0.01	0.98 ± 0.03	0.99 ± 0.02	0.99 ± 0.02	1.0 ± 0.0
		Proposed method	273.0	84.31 ± 6.53	11.22 ± 7.81	3.75 ± 3.78	0.72 ± 1.73	1.0 ± 0.01	0.99 ± 0.02	1.0 ± 0.0	0.99 ± 0.01	1.0 ± 0.0
			-64.0	-7%	+5%	+4%	-2%	0%	+1%	+1%	0%	0%
Low-Volt.	1-25	Baseline	91.0	40.9 ± 21.42	48.4 ± 21.07	6.8 ± 9.52	3.9 ± 4.9	0.98 ± 0.03	0.96 ± 0.06	0.97 ± 0.06	0.96 ± 0.07	1.0 ± 0.01
		Proposed method	89.0	65.42 ± 21.15	25.15 ± 21.86	4.73 ± 7.63	4.71 ± 4.66	0.99 ± 0.02	0.97 ± 0.04	0.99 ± 0.03	0.98 ± 0.04	1.0 ± 0.0
			-2.0	+25%	-23%	-2%	+1%	+1%	+1%	+2%	+2%	0%
	1-50	Baseline	174.0	50.45 ± 18.57	42.95 ± 16.13	3.4 ± 7.53	3.2 ± 4.68	0.99 ± 0.02	0.96 ± 0.06	0.98 ± 0.05	0.97 ± 0.06	1.0 ± 0.01
		Proposed method	143.0	70.73 ± 17.01	17.99 ± 18.79	5.69 ± 8.13	5.59 ± 5.01	0.99 ± 0.02	0.98 ± 0.04	0.99 ± 0.02	0.98 ± 0.03	1.0 ± 0.0
			-31.0	+20%	-25%	+2%	+2%	0%	+2%	+1%	+1%	0%
	1-75	Baseline	253.0	53.63 ± 16.33	41.13 ± 13.64	2.27 ± 6.35	2.97 ± 4.58	0.99 ± 0.02	0.97 ± 0.05	0.98 ± 0.04	0.97 ± 0.05	1.0 ± 0.01
		Proposed method	209.0	71.95 ± 15.03	16.32 ± 16.97	5.87 ± 8.59	5.86 ± 5.33	0.99 ± 0.01	0.98 ± 0.03	0.99 ± 0.02	0.99 ± 0.03	1.0 ± 0.0
			-44.0	+18%	-25%	+4%	+3%	0%	+1%	+1%	+2%	0%
	1-100	Baseline	337.0	55.22 ± 14.83	40.22 ± 12.11	1.7 ± 5.58	2.85 ± 4.52	0.99 ± 0.02	0.97 ± 0.05	0.99 ± 0.04	0.98 ± 0.05	1.0 ± 0.01
		Proposed method	273.0	72.71 ± 13.6	15.63 ± 15.82	5.67 ± 8.4	5.99 ± 5.4	0.99 ± 0.01	0.99 ± 0.03	1.0 ± 0.02	0.99 ± 0.03	1.0 ± 0.0
			-64.0	+17%	-25%	+4%	+3%	0%	+2%	+1%	+1%	0%

TABLE VI
ATTACK CLASSIFICATION FOR IEC61850-SECURITY DATASET (MULTICLASS)

Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC
High-Volt.	1-25	Baseline	102.0	0.25 ± 0.9	10.62 ± 6.29	21.61 ± 4.88	67.52 ± 7.66	0.51 ± 0.09	0.35 ± 0.05	0.36 ± 0.08	0.33 ± 0.06	0.64 ± 0.06
		Proposed method	100.0	0.95 ± 2.47	19.72 ± 7.49	29.23 ± 8.43	50.11 ± 4.56	0.57 ± 0.1	0.48 ± 0.12	0.52 ± 0.13	0.48 ± 0.12	0.75 ± 0.09
			-2.0	+1%	+9%	+8%	-17%	+6%	+13%	+16%	+15%	+11%
	1-50	Baseline	190.0	2.07 ± 2.77	16.97 ± 8.85	21.43 ± 5.53	59.53 ± 10.07	0.58 ± 0.1	0.42 ± 0.1	0.44 ± 0.11	0.42 ± 0.11	0.71 ± 0.09
		Proposed method	176.0	4.76 ± 5.04	23.98 ± 8.35	24.4 ± 8.8	46.85 ± 5.47	0.64 ± 0.12	0.55 ± 0.14	0.6 ± 0.15	0.56 ± 0.15	0.81 ± 0.1
			-14.0	+3%	+7%	+3%	-13%	+6%	+13%	+16%	+14%	+10%
	1-75	Baseline	284.0	3.83 ± 3.41	22.45 ± 11.15	19.3 ± 5.78	54.42 ± 11.31	0.63 ± 0.11	0.48 ± 0.12	0.52 ± 0.14	0.48 ± 0.13	0.76 ± 0.09
		Proposed method	240.0	5.56 ± 4.89	26.38 ± 8.97	23.13 ± 7.89	44.93 ± 6.25	0.69 ± 0.12	0.61 ± 0.14	0.65 ± 0.15	0.62 ± 0.15	0.85 ± 0.1
			-44.0	+2%	+4%	+4%	-9%	+6%	+13%	+13%	+14%	+9%
	1-100	Baseline	382.0	4.53 ± 3.19	25.53 ± 11.35	18.52 ± 5.72	51.42 ± 11.15	0.66 ± 0.11	0.52 ± 0.12	0.57 ± 0.15	0.53 ± 0.14	0.78 ± 0.09
		Proposed method	310.0	6.19 ± 4.68	28.92 ± 9.42	21.71 ± 7.64	43.18 ± 6.43	0.71 ± 0.12	0.64 ± 0.14	0.68 ± 0.14	0.64 ± 0.14	0.86 ± 0.1
			-72.0	+2%	+3%	+3%	-8%	+5%	+12%	+11%	+11%	+8%
Distribution	1-25	Baseline	102.0	0.0 ± 0.0	10.75 ± 6.06	18.04 ± 8.11	71.2 ± 8.33	0.46 ± 0.08	0.33 ± 0.07	0.33 ± 0.1	0.31 ± 0.07	0.63 ± 0.05
		Proposed method	100.0	1.81 ± 4.26	24.8 ± 14.94	27.73 ± 14.48	45.66 ± 8.95	0.55 ± 0.14	0.46 ± 0.14	0.49 ± 0.18	0.45 ± 0.15	0.74 ± 0.11
			-2.0	+2%	+14%	+10%	-26%	+9%	+13%	+16%	+14%	+11%
	1-50	Baseline	190.0	0.0 ± 0.0	11.0 ± 6.31	22.71 ± 13.41	66.3 ± 10.85	0.53 ± 0.1	0.38 ± 0.1	0.4 ± 0.12	0.37 ± 0.1	0.68 ± 0.08
		Proposed method	176.0	3.81 ± 5.7	25.47 ± 14.08	25.27 ± 12.1	45.45 ± 9.41	0.61 ± 0.14	0.52 ± 0.14	0.56 ± 0.17	0.52 ± 0.16	0.79 ± 0.11
			-14.0	+4%	+14%	+3%	-21%	+8%	+14%	+16%	+15%	+11%
	1-75	Baseline	284.0	0.0 ± 0.0	12.23 ± 6.81	24.48 ± 13.06	63.3 ± 11.69	0.57 ± 0.1	0.43 ± 0.11	0.46 ± 0.14	0.43 ± 0.11	0.71 ± 0.08
		Proposed method	240.0	2.98 ± 5.25	28.34 ± 14.06	24.34 ± 10.76	44.34 ± 9.32	0.66 ± 0.13	0.57 ± 0.15	0.62 ± 0.17	0.57 ± 0.16	0.82 ± 0.11
			-44.0	+3%	+16%	+0%	-19%	+9%	+14%	+16%	+14%	+11%
	1-100	Baseline	382.0	0.0 ± 0.0	13.81 ± 6.8	24.88 ± 12.39	61.31 ± 11.33	0.6 ± 0.1	0.46 ± 0.11	0.5 ± 0.14	0.46 ± 0.12	0.73 ± 0.08
		Proposed method	310.0	2.74 ± 4.85	30.21 ± 13.48	23.79 ± 10.35	43.26 ± 8.68	0.68 ± 0.13	0.59 ± 0.14	0.65 ± 0.17	0.6 ± 0.15	0.84 ± 0.1
			-72.0	+3%	+16%	-1%	-18%	+8%	+13%	+15%	+14%	+11%
Low-Volt.	1-25	Baseline	102.0	0.0 ± 0.0	10.94 ± 12.49	17.49 ± 10.04	71.56 ± 12.78	0.41 ± 0.09	0.29 ± 0.09	0.27 ± 0.1	0.27 ± 0.08	0.57 ± 0.08
		Proposed method	100.0	0.89 ± 4.48	21.43 ± 18.8	30.79 ± 15.14	46.9 ± 18.96	0.49 ± 0.14	0.42 ± 0.16	0.43 ± 0.18	0.4 ± 0.16	0.7 ± 0.12
			-2.0	+1%	+10%	+13%	-25%	+8%	+13%	+16%	+13%	+13%
	1-50	Baseline	190.0	0.0 ± 0.0	9.08 ± 10.98	21.52 ± 14.27	69.39 ± 12.17	0.43 ± 0.08	0.28 ± 0.08	0.28 ± 0.09	0.26 ± 0.08	0.58 ± 0.07
		Proposed method	176.0	2.43 ± 7.02	20.99 ± 16.89	28.3 ± 14.14	48.29 ± 16.63	0.52 ± 0.15	0.43 ± 0.17	0.45 ± 0.19	0.41 ± 0.17	0.71 ± 0.13
			-14.0	+2%	+12%	+7%	-21%	+9%	+15%	+17%	+15%	+13%
	1-75	Baseline	284.0	0.0 ± 0.0	9.53 ± 9.71	23.73 ± 13.69	66.74 ± 11.94	0.43 ± 0.08	0.28 ± 0.08	0.28 ± 0.09	0.26 ± 0.07	0.58 ± 0.07
		Proposed method	240.0	2.2 ± 6.43	21.3 ± 15.85	27.26 ± 13.11	49.24 ± 16.01	0.56 ± 0.16	0.46 ± 0.18	0.5 ± 0.22	0.46 ± 0.19	0.74 ± 0.14
			-44.0	+2%	+12%	+4%	-17%	+13%	+18%	+22%	+20%	+16%
	1-100	Baseline	382.0	0.0 ± 0.0	9.4 ± 8.67	24.77 ± 12.72	65.84 ± 11.08	0.43 ± 0.07	0.28 ± 0.07	0.28 ± 0.08	0.26 ± 0.07	0.57 ± 0.07
		Proposed method	310.0	2.46 ± 6.45	22.05 ± 15.03	26.45 ± 12.34	49.04 ± 14.59	0.58 ± 0.16	0.48 ± 0.18	0.53 ± 0.22	0.48 ± 0.19	0.76 ± 0.14
			-72.0	+2%	+13%	+2%	-17%	+15%	+20%	+25%	+22%	+19%

TABLE VII
ATTACK CLASSIFICATION FOR UNSW-NB15 DATASET (MULTICLASS)

Substation	Round	Strategy	Time [s]	Safe [%]	Borderline [%]	Rare [%]	Outlier [%]	Accuracy	Recall	Precision	F1-Score	AUC	
High-Volt.	1-25	Baseline	113.0	1.2 ± 1.27	47.8 ± 10.11	27.0 ± 9.97	24.0 ± 2.39	0.7 ± 0.04	0.57 ± 0.04	0.63 ± 0.03	0.58 ± 0.03	0.92 ± 0.01	
		Proposed method	96.0 -17.0	17.25 ± 8.0 +16%	55.18 ± 7.42 +7%	13.14 ± 2.99 -14%	14.44 ± 5.01 -10%	0.75 ± 0.11 +5%	0.67 ± 0.13 +10%	0.69 ± 0.13 +6%	0.67 ± 0.13 +9%	0.93 ± 0.05 +1%	
	1-50	Baseline	215.0	2.0 ± 1.34	39.55 ± 11.9	28.05 ± 7.66	30.4 ± 7.08	0.76 ± 0.07	0.62 ± 0.06	0.67 ± 0.06	0.63 ± 0.06	0.94 ± 0.02	
		Proposed method	158.0 -57.0	15.57 ± 9.06 +14%	49.2 ± 9.47 +10%	16.77 ± 6.77 -11%	18.46 ± 6.25 -12%	0.81 ± 0.1 +5%	0.74 ± 0.12 +12%	0.77 ± 0.12 +10%	0.74 ± 0.12 +11%	0.96 ± 0.05 +2%	
	1-75	Baseline	324.0	7.2 ± 10.19	40.07 ± 9.84	23.6 ± 9.78	29.13 ± 7.16	0.79 ± 0.07	0.65 ± 0.07	0.7 ± 0.07	0.66 ± 0.07	0.95 ± 0.02	
		Proposed method	245.0 -79.0	16.56 ± 8.15 +9%	46.31 ± 9.35 +6%	17.12 ± 6.48 -6%	20.01 ± 5.96 -9%	0.83 ± 0.09 +4%	0.76 ± 0.11 +11%	0.78 ± 0.11 +8%	0.76 ± 0.11 +10%	0.97 ± 0.04 +2%	
	1-100	Baseline	457.0	7.54 ± 10.84	38.26 ± 9.98	22.79 ± 9.83	31.41 ± 9.19	0.82 ± 0.08	0.67 ± 0.08	0.73 ± 0.07	0.68 ± 0.08	0.96 ± 0.02	
		Proposed method	347.0 -110.0	21.56 ± 12.14 +14%	45.93 ± 9.09 +8%	14.38 ± 7.82 -8%	18.12 ± 6.52 -13%	0.85 ± 0.09 +3%	0.77 ± 0.1 +10%	0.8 ± 0.1 +7%	0.77 ± 0.1 +9%	0.97 ± 0.04 +1%	
	Distribution	1-25	Baseline	113.0	2.5 ± 2.53	38.8 ± 4.23	33.2 ± 4.71	25.5 ± 4.43	0.68 ± 0.06	0.56 ± 0.07	0.58 ± 0.09	0.55 ± 0.07	0.91 ± 0.03
			Proposed method	96.0 -17.0	12.6 ± 10.73 +10%	58.18 ± 10.9 +19%	14.35 ± 8.77 -19%	14.87 ± 9.33 -11%	0.79 ± 0.1 +11%	0.71 ± 0.13 +15%	0.74 ± 0.13 +16%	0.71 ± 0.13 +16%	0.96 ± 0.03 +5%
		1-50	Baseline	215.0	1.25 ± 2.18	36.85 ± 9.45	24.05 ± 12.18	37.85 ± 15.15	0.73 ± 0.07	0.59 ± 0.07	0.63 ± 0.09	0.58 ± 0.08	0.93 ± 0.03
			Proposed method	158.0 -57.0	11.93 ± 11.28 +11%	49.41 ± 15.36 +13%	18.59 ± 11.07 -5%	20.07 ± 11.64 -18%	0.83 ± 0.09 +10%	0.75 ± 0.12 +16%	0.79 ± 0.12 +16%	0.75 ± 0.12 +17%	0.97 ± 0.03 +4%
1-75		Baseline	324.0	0.83 ± 1.87	45.77 ± 16.36	19.73 ± 12.12	33.67 ± 15.57	0.76 ± 0.08	0.61 ± 0.07	0.66 ± 0.09	0.61 ± 0.08	0.94 ± 0.03	
		Proposed method	245.0 -79.0	12.9 ± 12.24 +12%	46.75 ± 14.87 +1%	18.39 ± 10.24 -1%	21.97 ± 10.55 -12%	0.85 ± 0.09 +9%	0.77 ± 0.12 +16%	0.81 ± 0.12 +15%	0.78 ± 0.13 +17%	0.97 ± 0.03 +3%	
1-100		Baseline	457.0	0.62 ± 1.66	41.48 ± 20.69	19.64 ± 12.24	38.25 ± 18.69	0.78 ± 0.08	0.62 ± 0.07	0.69 ± 0.09	0.63 ± 0.08	0.95 ± 0.03	
		Proposed method	347.0 -110.0	13.39 ± 12.02 +13%	48.4 ± 14.62 +7%	17.53 ± 10.06 -2%	20.68 ± 10.05 -18%	0.86 ± 0.08 +8%	0.78 ± 0.11 +16%	0.82 ± 0.11 +13%	0.78 ± 0.12 +15%	0.98 ± 0.02 +3%	
Low-Volt.		1-25	Baseline	113.0	0.0 ± 0.0	15.4 ± 12.26	36.5 ± 11.14	48.1 ± 9.29	0.58 ± 0.1	0.47 ± 0.09	0.44 ± 0.09	0.42 ± 0.08	0.88 ± 0.04
			Proposed method	96.0 -17.0	10.5 ± 15.69 +10%	52.2 ± 18.98 +37%	19.91 ± 16.05 -17%	17.4 ± 11.51 -31%	0.79 ± 0.12 +21%	0.73 ± 0.15 +26%	0.75 ± 0.16 +31%	0.71 ± 0.17 +29%	0.95 ± 0.05 +7%
		1-50	Baseline	215.0	0.0 ± 0.0	21.35 ± 15.75	33.35 ± 11.49	45.3 ± 13.48	0.61 ± 0.09	0.46 ± 0.09	0.45 ± 0.1	0.43 ± 0.09	0.88 ± 0.04
			Proposed method	158.0 -57.0	10.24 ± 15.98 +10%	48.77 ± 19.11 +27%	19.81 ± 14.97 -14%	21.18 ± 12.73 -24%	0.82 ± 0.11 +21%	0.75 ± 0.15 +29%	0.79 ± 0.15 +34%	0.74 ± 0.15 +31%	0.96 ± 0.04 +8%
	1-75	Baseline	324.0	0.0 ± 0.0	29.4 ± 22.45	27.97 ± 15.8	42.63 ± 15.73	0.64 ± 0.09	0.45 ± 0.09	0.45 ± 0.1	0.42 ± 0.08	0.89 ± 0.04	
		Proposed method	245.0 -79.0	9.77 ± 15.22 +10%	46.76 ± 18.86 +17%	19.51 ± 14.37 -8%	23.96 ± 12.59 -19%	0.83 ± 0.11 +19%	0.76 ± 0.15 +31%	0.79 ± 0.15 +34%	0.75 ± 0.16 +33%	0.96 ± 0.04 +7%	
	1-100	Baseline	457.0	0.0 ± 0.0	26.97 ± 22.48	27.02 ± 16.29	46.01 ± 18.83	0.66 ± 0.09	0.44 ± 0.08	0.45 ± 0.09	0.42 ± 0.07	0.89 ± 0.04	
		Proposed method	347.0 -110.0	8.74 ± 14.38 +9%	47.74 ± 18.18 +21%	19.66 ± 14.36 -7%	23.86 ± 11.84 -22%	0.82 ± 0.1 +16%	0.74 ± 0.16 +30%	0.77 ± 0.16 +32%	0.73 ± 0.16 +31%	0.96 ± 0.04 +7%	

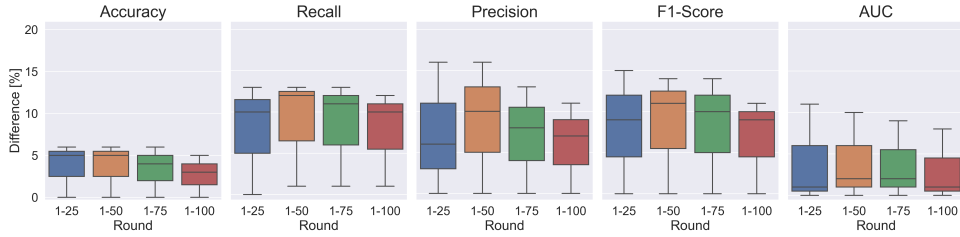
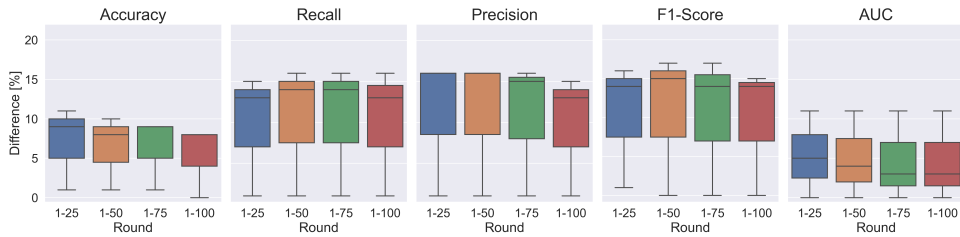
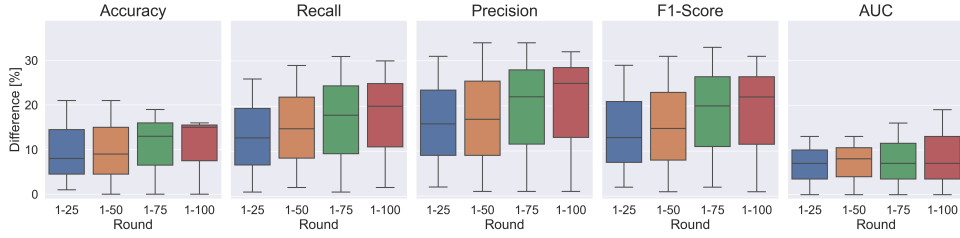


Fig. 2. Gain between the baseline and proposed method for each substation (multiclass scenario) – different colors represent different time blocks