Mixed Integer Programing(MIP)-Based Fault Location Identification Using MicroPMUs

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Outline

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Utility performance evaluation

- Nowadays, the electric utility industry is a competitive field. Each utility wants to increase productivity and reduce economic losses.
- Reliability indices are a way of evaluating the performance of the utilities. To be a competitive in the utilities market, improve these indices.
- Accoring to IEEE Std 1366 (IEEE Guide for Electric Power Distribution Reliability Indices).
  - The System Average Interruption Duration Index (SAIDI)=

$$\frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Served Customers}}$$

  - The Customer Average Interruption Duration Index (CAIDI)=

$$\frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Served Customers}}$$

- Reducing the interruption duration will ensure improvement in these indices.

A Common Used Method

Impedance Based Method [1]

- Uses voltage and current measurements at the substation to estimate the impedance and then the distance to the fault point.
- a standard feature in most microprocessor-based relays.
- Adopted from the transmission system.
- In Distribution systems, The method suffers from multi-estimation due to the radial topology of the system (multiple points may have the same distance.)

Common practices to improve it: to use external information to narrow the searching area

- History of events
- Weather status
- Construction areas
- Costumers calls!! (Do we really want to wait for an angry customer call?!)

[1] (J. Mora-Florez, J. Melendez, and G. Carrillo-Caicedo, "Comparison of impedance based fault location methods for power distribution systems," Electric Power Systems Research, vol. 78, no. 4, pp. 657–666, 2008)

Example[2]

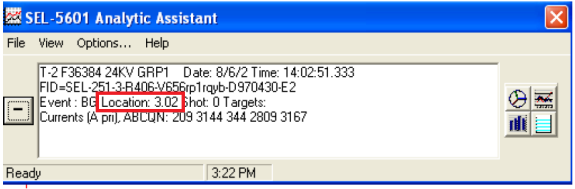

Figure: Fault event screen capture

							Cumulative Per Unit Impedance					Calculated Fault Currents at the end of this branch					Per Unit Impedance for this conductor or Transformer				{Cumulative Line Z Ohms}		Percent Impedance per 1000 feet	
1	FEEDER T2	36384	Source Line +				0.0114 +j 0.2487		0.0080 +j 0.2201			8850	9204	13997	14557	21.92								
TO NODE Number	Table Name	Wire Size	feet	Order FRO M	FRO M	Miles from Source	R1 +j X1		R0 +j X0		I3	Iph-g	Assym. I3	Assym. Iph-g	X/R	R1 +j X1		R0 +j X0		R1+j X1	R0+j X0	R1 +j X1		R0 +j X0	
2	CD_28kV_XLPE	750	690			0.13	0.0142 +j 0.2552		0.0204 +j 0.2239		8622	8983	13387	13947	18.00	0.0028	0.0064	0.0124	0.0038	0.002+j0.004	0.009+j0.003	0.4094 +j 0.9338		1.7933 +j 0.5448	
3	DB_28kV_XLPE	500	2800			0.66	0.0362 +j 0.2753		0.0751 +j 0.2377		7937	8217	10867	11250	7.59	0.0221	0.0201	0.0547	0.0138	0.196+j0.109	0.292+j0.074	0.7881 +j 0.7167		1.9536 +j 0.4924	
4	OH_XARM	336 ACSR	3062			1.24	0.0599 +j 0.3306		0.1380 +j 0.3978		6559	6248	8402	7748	5.52	0.0236	0.0553	0.0629	0.1601	0.227+j0.478	0.609+j1.684	0.7721 +j 1.8210		1.5588 +j 7.3249	
5	DB_28kV_XLPE	500	906			1.41	0.0670 +j 0.3371		0.1557 +j 0.4023		6412	5910	8043	7413	5.03	0.0071	0.0065	0.0177	0.0045	0.387+j0.747	0.839+j2.855	0.7721 +j 1.8210		1.5588 +j 7.3249	
6	DB_28kV_XLPE	500	1973			1.79	0.0826 +j 0.3512		0.1942 +j 0.4120		6108	5617	7372	6778	4.25	0.0155	0.0141	0.0385	0.0097	0.527+j0.1076	1.121+j4.285	0.7721 +j 1.8210		1.5588 +j 7.3249	
7	OH_XARM	336 ACSR	2684			2.29	0.1033 +j 0.3997		0.2494 +j 0.5524		5338	4618	6303	5452	3.87	0.0207	0.0485	0.0551	0.1404	0.560+j1.154	1.187+j4.623	0.7721 +j 1.8210		1.5588 +j 7.3249	
8	OH_XARM	336 ACSR	649			2.40	0.1083 +j 0.4114		0.2627 +j 0.5863		5180	4427	6090	5205	3.80	0.0050	0.0117	0.0133	0.0339	1.229+j1.535	1.892+j6.055	3.8896 +j 2.2143		4.6763 +j 8.3183	
9	OH_XARM	336 ACSR	2096			2.81	0.1245 +j 0.4493		0.3058 +j 0.6959		4727	3906	5493	4539	3.61	0.0162	0.0379	0.0431	0.1096	0.651+j1.369	1.372+j5.561	0.7721 +j 1.8210		1.5588 +j 7.3249	
10	OH_XARM	336 ACSR	2506			3.29	0.1438 +j 0.4945		0.3572 +j 0.8270		4279	3424	4919	3936	3.44	0.0193	0.0453	0.0515	0.1311	0.868+j1.409	1.405+j5.732	0.7721 +j 1.8210		1.5588 +j 7.3249	
11	OH_XARM	336 ACSR	1377	7		2.56	0.1139 +j 0.4246		0.2777 +j 0.6244		5013	4231	5863	4953	3.73	0.0106	0.0249	0.0283	0.0720	0.852+j1.843	1.777+j7.624	0.7721 +j 1.8210		1.5588 +j 7.3249	
12	OH_XARM	336 ACSR	4025	7		3.06	0.1344 +j 0.4724		0.3321 +j 0.7629		4487	3644	5184	4210	3.52	0.0311	0.0727	0.0827	0.2105	0.805+j1.734	1.683+j7.147	0.7721 +j 1.8210		1.5588 +j 7.3249	
13	OH_XARM	1/0 ACSR	1115			3.27	0.1617 +j 0.4958		0.3809 +j 0.8355		4226	3371	4739	3780	3.07	0.0273	0.0234	0.0489	0.0726	0.863+j1.870	1.801+j7.742	0.7721 +j 1.8210		1.5588 +j 7.3249	
14	OH_XARM	336 ACSR	961	12		3.24	0.1418 +j 0.4898		0.3519 +j 0.8121		4322	3469	4974	3992	3.45	0.0074	0.0174	0.0197	0.0503	0.955+j2.088	1.985+j8.679	0.7721 +j 1.8210		1.5588 +j 7.3249	
15	DB_28kV_XLPE	500	778			3.39	0.1479 +j 0.4953		0.3670 +j 0.8170		4263	3426	4892	3916	3.35	0.0061	0.0056	0.0152	0.0038	0.708+j1.504	1.487+j6.146	0.7721 +j 1.8210		1.5588 +j 7.3249	
16	OH_XARM	336 ACSR	1459			3.66	0.1592 +j 0.5217		0.3970 +j 0.8933		4040	3196	4596	3636	3.28	0.0113	0.0264	0.0300	0.0763	0.824+j1.777	1.720+j7.334	0.7721 +j 1.8210		1.5588 +j 7.3249	
17	OH_XARM	336 ACSR	1129			3.88	0.1679 +j 0.5421		0.4201 +j 0.9523		3883	3038	4403	3445	3.23	0.0087	0.0204	0.0232	0.0590	0.891+j1.934	1.895+j8.020	0.7721 +j 1.8210		1.5588 +j 7.3249	
18	OH_XARM	336 ACSR	578			3.99	0.1724 +j 0.5525		0.4320 +j 0.9825		3807	2963	4310	3355	3.21	0.0045	0.0104	0.0119	0.0302	0.971+j2.124	2.018+j8.945	0.7721 +j 1.8210		1.5588 +j 7.3249	
19	OH_XARM	336 ACSR	412	16		3.74	0.1624 +j 0.5291		0.4054 +j 0.9148		3981	3137	4523	3564	3.26	0.0032	0.0074	0.0085	0.0215	1.131+j2.500	2.340+j10.484	0.7721 +j 1.8210		1.5588 +j 7.3249	
20	OH_XARM	336 ACSR	3850			4.47	0.1921 +j 0.5987		0.4845 +j 1.1162		3505	2672	3944	3007	3.12	0.0297	0.0695	0.0791	0.2014	1.202+j2.565	2.517+j10.528	0.7881 +j 0.7167		1.9536 +j 0.4924	
21	OH_XARM	336 ACSR	4834			5.39	0.2294 +j 0.6808		0.5830 +j 1.3530		3046	2262	3359	2513	2.93	0.0373	0.0873	0.0993	0.2528	1.224+j2.649	2.745+j10.536	0.7881 +j 0.7167		1.9536 +j 0.4924	
22	OH_XARM	336 ACSR	2735	20		4.99	0.2132 +j 0.6481		0.5407 +j 1.2592		3230	2417	3616	2706	3.04	0.0211	0.0494	0.0562	0.1430	1.330+j2.682	2.835+j10.608	0.7881 +j 0.7167		1.9536 +j 0.4924	
23	OH_XARM	336 ACSR	2571			5.47	0.2331 +j 0.6945		0.5935 +j 1.3937		3008	2218	3353	2473	2.98	0.0199	0.0464	0.0528	0.1345	1.358+j2.707	2.904+j10.626	0.7881 +j 0.7167		1.9536 +j 0.4924	

Figure: Spreadsheet for the line parameters

[2] (K. Zimmerman and D. Costello, "Impedance-based fault location experience," in Proc. 58th Annu. Conf. Protect. Relay Eng., Apr. 2005, pp. 211–226)

Continue

Two Possible locations

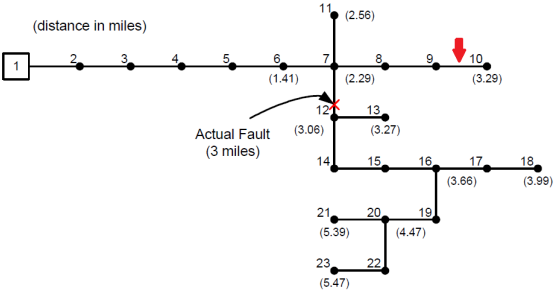

Figure: Distribution Feeder

IEEE-123

How many points will have the same distance to the substation?

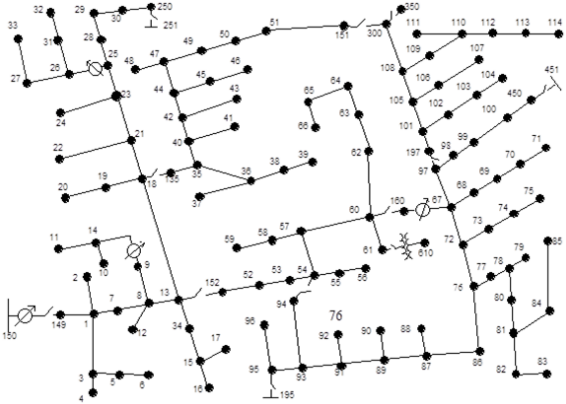

Figure: IEEE-123 test feeder

Our objective

- To reduce the outage time in order to improve the reliability indices and reduce revenue loss caused by outages.
- To achieve that goal: a fast fault location method is required to speed up the restoration process.

Outline

The Advantages of the MIP-Based Proposed method

- Does not yield to multiple locations.
- Only requires the pre and during fault voltages at the end of the branches in addition to the impedance bus matrix. (no need for current measurements)
- Applicable for grounded and ungrounded systems.
- The implementation of the proposed method is simple and does not require multiple stages or iterations.
- It determines the fault type, location and magnitude. While other methods rely on protective devises in substations to classify the fault type or determine the fault magnitude.

Outline

MIP Formulation for a Simple Single Phase Network

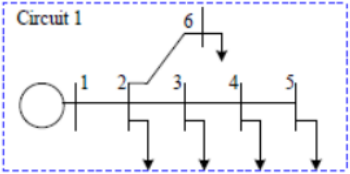

Figure: Simple 6-Node Network

$$\begin{bmatrix} 0 & 0 & -\bar{I}_{f4} & 0 & 0 \end{bmatrix}^T = Y_{NN}\Delta\bar{V}_N \quad (1)$$

$$\Delta\bar{V} = \bar{V}^{\text{post}} - \bar{V}^{\text{pre}}$$

$$\Delta\bar{V}_N = Z_{NN}\begin{bmatrix} 0 & 0 & -\bar{I}_{f4} & 0 & 0 \end{bmatrix}^T \quad (2)$$

Only one voltage phasor is required to find $\bar{I}_{f4}$, if more than one voltage phasors are measured, it will be an overdetermined problem.

$$Z_{NN} = \begin{bmatrix} z_{12} & z_{12} & z_{12} & z_{12} & z_{12} \\ z_{12} & z_{12}+z_{23} & z_{12}+z_{23} & z_{12}+z_{23} & z_{12} \\ z_{12} & z_{12}+z_{23} & z_{12}+z_{23}+z_{34} & z_{12}+z_{23}+z_{34} & z_{12} \\ z_{12} & z_{12}+z_{23} & z_{12}+z_{23}+z_{34} & z_{12}+z_{23}+z_{34}+z_{45} & z_{12} \\ z_{12} & z_{12} & z_{12} & z_{12} & z_{26} \end{bmatrix}$$

MIP Formulation For a Simple Single Phase Network

- Now we will assume that the fault location and magnitude are unknown.
- Hence a binary variable is introduced for each bus u_i as shown in (3). If there a fault on bus i then u_i=1 , If not $u_i = 0$

$$\Delta \bar{V}_N = Z_{NN} \begin{bmatrix} -u_2 \bar{I}_{f2} & -u_3 \bar{I}_{f3} & -u_4 \bar{I}_{f4} & -u_5 \bar{I}_{f5} & -u_6 \bar{I}_{f6} \end{bmatrix}^T \tag{3}$$

MIP Formulation For a Simple Single Phase Network

- Now will replace $u_i \bar{I}_{fi}$ with $\bar{I}_{xi}$

$$\Delta \bar{V}_N = Z_{NN} \begin{bmatrix} -\bar{I}_{x2} & -\bar{I}_{x3} & -\bar{I}_{x4} & \bar{I}_{x5} & \bar{I}_{x6} \end{bmatrix}^T \tag{4}$$

$$\bar{I}_{xi} = \begin{cases} \bar{I}_{fi}, & \text{if } u_i = 1 \\ 0, & \text{if } u_i = 0 \end{cases} \tag{5}$$

- If the system has only one fault, then the inequality constrains is imposed

$$\sum_{i=2}^{6} u_i \leq 1 \tag{6}$$

MIP formulation for a simple single phase network

- Note that I_f is a phasor so its real and imaginary parts will be considered separately using the big-M technique as shown in (6)

$$
\begin{aligned}
&-(1-u_i)M + \mathsf{Re}(\bar{I}_{fi}) \leq \mathsf{Re}(\bar{I}_{xi}) \leq \mathsf{Re}(\bar{I}_{fi}) + (1-u_i)M \\
&-(1-u_i)M + \mathsf{Im}(\bar{I}_{fi}) \leq \mathsf{Im}(\bar{I}_{xi}) \leq \mathsf{Im}(\bar{I}_{fi}) + (1-u_i)M \\
&-u_i M \leq \mathsf{Re}(\bar{I}_{xi}) \leq +u_i M \\
&-u_i M \leq \mathsf{Im}(\bar{I}_{xi}) \leq +u_i M
\end{aligned}
\tag{7}
$$

if $u_i = 1$

$$
\begin{aligned}
Re(\bar{I}_{xi}) &= Re(\bar{I}_{fi}) \\
Im(\bar{I}_{xi}) &= Im(\bar{I}_{fi}) \\
-M &\leq \mathsf{Re}(\bar{I}_{xi}) \leq M \\
-M &\leq \mathsf{Im}(\bar{I}_{xi}) \leq M
\end{aligned}
$$

if $u_i = 0$

$$
\begin{aligned}
Re(\bar{I}_{xi}) &= 0 \\
Im(\bar{I}_{xi}) &= 0
\end{aligned}
$$

The Overall MIP Problem Formulation

- The objective function is the sum of the norm 2 of the error between the measured and estimated voltage deviation values.
- The measured voltage values are collected using MicroPMUs located at the end of the branched + the first bus after the source bus.

$$\text{minimize} \sum_{i \in \mathcal{E}} \| \Delta \bar{V}_i^{\text{meas}} - \Delta \bar{V}_i \| \tag{8a}$$

$$\text{subject to} \sum_{i \in \mathcal{N}} u_i \leq 1 \tag{8b}$$

$$\Delta \bar{V}_N = -Z_{NN} \bar{I}_x \tag{8c}$$

$$-u_i M \leq \text{Re}(\bar{I}_{xi}) \leq +u_i M \tag{8d}$$

$$-u_i M \leq \text{Im}(\bar{I}_{xi}) \leq +u_i M \tag{8e}$$

$$-(1-u_i)M + \text{Re}(\bar{I}_{fi}) \leq \text{Re}(\bar{I}_{xi}) \leq \text{Re}(\bar{I}_{fi}) + (1-u_i)M \tag{8f}$$

$$-(1-u_i)M + \text{Im}(\bar{I}_{fi}) \leq \text{Im}(\bar{I}_{xi}) \leq \text{Im}(\bar{I}_{fi}) + (1-u_i)M \tag{8g}$$

$$\tag{8h}$$

where $\mathcal{E}$ is the set of the buses located at the end of each branch and the bus closest to the substation bus, $\mathcal{N}$ is the set of the buses except the substation bus.

Outline

MIP Formulation for Three-Phase Distribution Systems

- If three phase fault occurs at Bus4, the faults currents can be calculated as shown in (8).

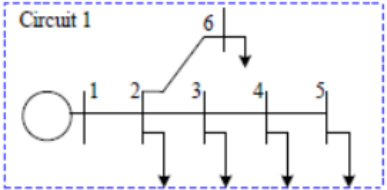

Figure: Simple 6-Node Network

$$\begin{bmatrix} 0 \\ \vdots \\ 0 \\ -\bar{I}^a_{f4} \\ -\bar{I}^b_{f4} \\ -\bar{I}^c_{f4} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = Y^{abc}_{NN} \begin{bmatrix} \Delta\bar{V}^a_2 \\ \Delta\bar{V}^b_2 \\ \Delta\bar{V}^c_2 \\ \vdots \\ \Delta\bar{V}^a_6 \\ \Delta\bar{V}^b_6 \\ \Delta\bar{V}^c_6 \end{bmatrix} \tag{9}$$

A fault location binary variable u_i is designated to each phase in each bus except substation bus

$$\Delta\bar{V}^{abc}_N = Z^{abc}_{NN} \begin{bmatrix} -u_2\bar{I}^a_{f2} \\ -u_3\bar{I}^b_{f2} \\ -u_4\bar{I}^c_{f2} \\ \vdots \\ -u_{14}\bar{I}^a_{f6} \\ -u_{15}\bar{I}^b_{f6} \\ -u_{16}\bar{I}^c_{f6} \end{bmatrix} \tag{10}$$

MIP Formulation For Three-Phase Distribution Systems

- To exclude the possibility of having faults between phases from different buses, Another location binary variable k_i is designated to each bus except the substation bus.
- For the 6-node network, The dimension of u is 15, and the dimension of k is 5.

$$\begin{aligned} u_2 + u_3 + u_4 &= 3(k_2) \\ u_5 + u_6 + u_7 &= 3(k_3) \\ u_8 + u_9 + u_{10} &= 3(k_4) \\ u_{11} + u_{12} + u_{13} &= 3(k_5) \\ u_{14} + u_{15} + u_{16} &= 3(k_6) \end{aligned} \tag{11}$$

$$\sum k_i = 1 \tag{12}$$

- When a fault happened at Bus 2 , $k_2 = 1$ and all the phase binaries at that bus are equal to 1, however that does not mean all the phases are under fault.
- The magnitude of the current will determine the faulted phase.

The Overall Three-Phase MIP Problem Formulation

$$\text{minimize} \sum_{i \in \mathcal{E}} \|\Delta \bar{V}_i^{abc,meas} - \Delta \bar{V}_i^{abc}\|$$

$$\text{subject to} \quad \Delta \bar{V}_N^{abc} = -Z_{NN}^{abc} \bar{I}_x^{abc} \tag{13a}$$

$$-u_i M \leq \text{Re}(\bar{I}_{xi}) \leq +u_i M \tag{13b}$$

$$-u_i M \leq \text{Im}(\bar{I}_{xi}) \leq +u_i M \tag{13c}$$

$$-(1-u_i)M + \text{Re}(\bar{I}_{fi}) \leq \text{Re}(\bar{I}_{xi}) \leq \text{Re}(\bar{I}_{fi}) + (1-u_i)M \tag{13d}$$

$$-(1-u_i)M + \text{Im}(\bar{I}_{fi}) \leq \text{Im}(\bar{I}_{xi}) \leq \text{Im}(\bar{I}_{fi}) + (1-u_i)M \tag{13e}$$

$$\text{for all } i \in \mathcal{B}$$

$$u_a + u_b + u_c = 3(k_i) \tag{13f}$$

$$\sum_{i \in \mathcal{E}} k_i = 1 \tag{13g}$$

$$\text{for all } i \in \mathcal{N}$$

where $\mathcal{E}$ is the set of the microPMU phases, $\mathcal{N}$ is the set of the buses except the substation bus. $\mathcal{B}$ is the set of the phases except the substation bus's phases.

Outline

Numerical example

- Very unbalanced feeder.
- (PQ,I and Z) loads.
- Ungrounded
- micro-PMUs are placed at the end of the branches as shown in the figure.

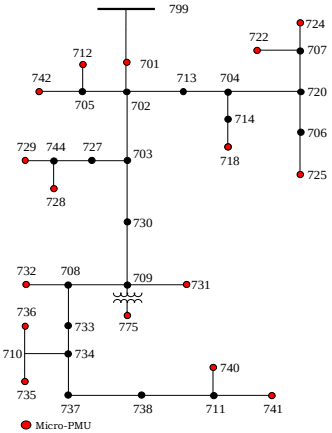

Figure: Modified version IEEE-37 Test Feeder

Numerical example

- All the single phase faults were identified correctly. (108 tests for each transformer configuration)

Table: Phase-to-Ground faults (Δ - Δ)

Location	Identification Results			OpenDSS Measurements	
	Obj	I_F	$\angle \bar{I}_F$	I_{flow}	$\angle \bar{I}_{\text{flow}}$
729.b	0.070	2.111	-36	2.225	-33.5
711.c	0.170	2.064	-158.9	2.188	-156.1
702.b	0.053	2.124	-36	2.240	-33.5
775.a	0.002	$4.9e10^{-4}$	-97.5	$5.3e10^{-4}$	-94.2

Table: Phase-to-Ground faults (Δ - Y)

Location	Identification Results			OpenDSS Measurements	
	Obj	I_F	$\angle \bar{I}_F$	I_{flow}	$\angle \bar{I}_{\text{flow}}$
702.a	89.6	2636.2	-100.4	2832.9	-97.3
741.c	100.2	1210	38.5	1285.4	41.5
707.b	94.2	1513	159.8	1591.9	162.2
710.c	99.88	1414.1	36.9	1503.3	39.9

Double and Three Phase faults

- More than 97% of the double and Three-phase faults were identified correctly.
- Only 2-3p Faults at 707 were identified as faults at Bus 722, which is adjacent bus to Bus 707. By excluding Bus 722 from the searching space, the proposed method correctly identified the faulted bus, which means it was at the second least objective function value.

Double and Three Phase Faults

Table: Double-Phase to Ground faults (Δ - Δ)

Location	Identification Results			OpenDSS Measurements	
	Obj	I_F^a	I_F^b	I_{flow}^a	I_{flow}^b
736.ab	155.1	1147.7	1168.5	1263.8	1262.9
714.ab	165.8	1992.8	2027.1	2191.5	2191
742.ab	153.3	1954.4	1990	2151.1	2150.4
775.ab	39.07	10630.7	10869.4	11796	11796

Table: Three-Phase Faults (Δ - Δ)

Location	Identification Results				OpenDSS Measurements		
	Obj	I_F^a	I_F^b	I_F^c	I_{flow}^a	I_{flow}^b	I_{flow}^c
727.abc	131.69	2231.8	2377.5	2242	2500.8	2573.9	2434.4
708.abc	140.2	1998.6	2159.2	2027.1	2242.2	2337.3	2197.2
738.abc	216.4	1545.8	1715.9	1606.5	1741.1	1859.7	1738.3
720.abc	257	2030.3	2188.6	2070.9	2261.3	2366.7	2253.6

Table: Double-Phase Faults (Δ - Y)

Location	Identification Results			OpenDSS Measurements	
	Obj	I_F^a	I_F^b	I_{flow}^a	I_{flow}^b
735.ab	140.6	1581.4	1446.2	1706.4	1583.4
704.ab	172.7	2407.3	2172	2576.5	2375.5
728.ab	119	2150.6	1934.4	2309.4	2120.3
731.ab	84.5	2018.3	1788.3	2171.7	1962

Table: Three-phase faults (Δ - Y)

Location	Identification Results				OpenDSS Measurements		
	Obj	I_F^a	I_F^b	I_F^b	I_{flow}^a	I_{flow}^b	I_{flow}^b
725.abc	265	1757.7	1904.1	1807.7	1956.6	2059.5	1966.6
744.abc	152.7	2142.3	2282.5	2152.9	2399.9	2472.2	2336.3
732.abc	153.2	1864.8	2015.8	1899.3	2092.1	2182.2	2058.3
737.abc	204	1631.1	1787.8	1683.1	1836.2	1938.5	1820.9

THANK YOU