Multi-objective Optimization Aiming to Minimize the Number of Power Quality Monitors and Multiple Fault Estimations in Unbalanced Power Distribution Systems

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• Recently published article:

- MARTINS, P. E. T. and OLESKOVICZ, M. Multi-objective optimization aiming to minimize the number of power quality monitors and multiple fault estimations in unbalanced power distribution systems. **IEEE Transactions on Power Delivery, vol. 37, no. 2, pp. 1315—1323, 2022.**

• Topics

- Introduction and contributions
- Methodology
- Results and discussion
- Conclusions

• Introduction and contributions

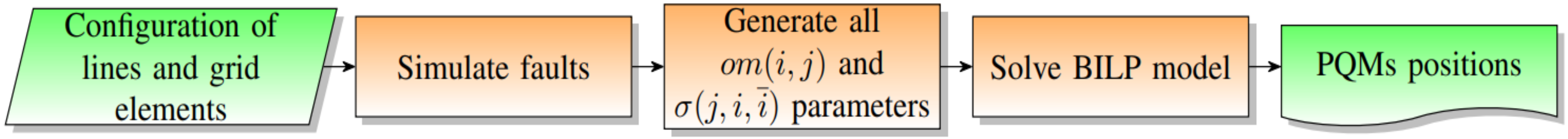
- **Several papers in transmission systems**: the **best locations** to install power quality monitors, **minimizing the investment cost** by focusing on the **observability of power quality disturbances**, mostly voltage sags.

- **Papers in distribution systems**: many problems remain unsolved, such as power quality monitor allocation in **unbalanced distribution systems**, the impact of **distributed generation** in allocation methods, and allocation of power quality monitor for **fault location**.

- **This paper** makes contributions to all these three points.

- The allocation method is based only on the **root mean square voltages (Vrms)** measured at the buses.

• Methodology



- Step 1: Configuration of lines and grid elements;
- Step 2: Fault simulations;
- Step 3: Generate binary parameters BILP (Binary Integer Linear Programming) model;
- Step 4: Solve the BILP model; and
- Step 5: PQMs positions.

• Methodology

• Step 1: Configuration of lines and grid elements

- This step builds an **electrical model for the PDS** from a database containing information on the types of cables, geometries and spacing in the towers, among other data. This model consists of self and mutual impedances, which allow the **PDS representation in fault simulations**.

- This paper considered the **European Medium Voltage System of 15 buses** proposed by **CIGRÉ** for the tests. Moreover, the method was applied to the **IEEE 123-bus Test System**. Finally, we considered a large, médium voltage PDS named **Ckt5 with 2998 buses of EPRI**.

• Methodology

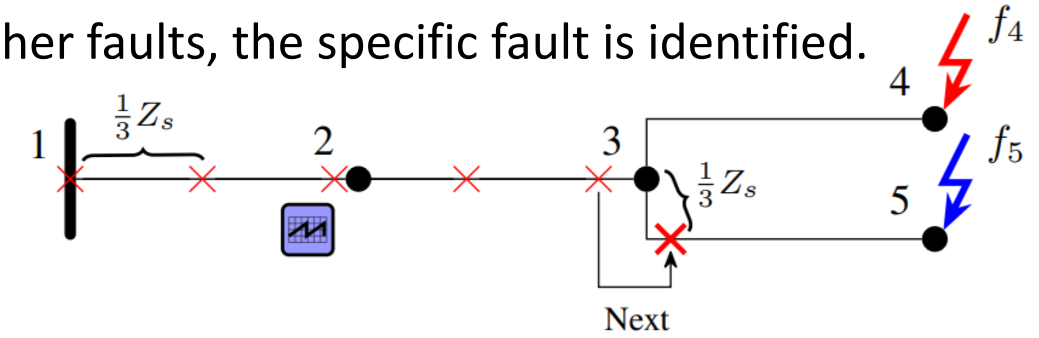
• Step 2: Fault simulations

- The fault simulations were carried out by implementing a **fault analysis program** and by using the **OpenDSS software** (Version 9.2.0.1).
- The database can also be obtained with any transient analysis software without any changes in the allocation method.
- We considered **no-load conditions** for the **CIGRÉ** and the **IEEE systems**. However, **load conditions** were considered for the **EPRI system**.
- The faults were uniformly distributed with a simulation step of **one third of the branch with the smallest impedance**.

• Methodology

• Step 3: Generate binary parameters

- The optimization problem was described as a Binary Integer Linear Programming (BILP) problem with two objectives: to **minimize the number of PQMs** and to **maximize the number of identified faults**.
- A particular fault is identified when installed PQMs can differentiate this fault from all other simulated faults.
- **The concept adopted** is that two faults that produce similar residual voltage at a particular measurement bus are called **symmetrical faults**.
- The voltages were compared using a specified range around these faults' voltage, where any voltage within the specified range is considered the same voltage (**symmetry condition**).
- If the set of PQMs can break the symmetry of all other faults, the specific fault is identified.



• Methodology

• Step 3: Generate binary parameters

TABLE I
SUGGESTED PRIORITY ORDER FOR CHOOSING THE REFERENCE PHASE

Fault Type	AT, AB, ABT, ABC	BT	CT, AC, ACT	BC, BCT
Priority order	A, B, C	B, A, C	C, A, B	B, C, A

$$\sigma(j,i,\bar{i}) \equiv \begin{cases} 0, & v(i,j)-\zeta \leq v(\bar{i},j) \geq v(i,j)+\zeta \\ 1, & \text{otherwise} \end{cases} \quad (3)$$

$$y(i) \equiv \begin{cases} 1, & \text{if } i \text{ fault is identified} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

$$x(j) \equiv \begin{cases} 1, & \text{if installing a PQM at the } j \text{ bus} \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

$$om(i,j) \equiv \begin{cases} 1, & v(i,j) \leq \tau \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$t^k(j) \equiv \begin{cases} 1, & \text{if } k \text{ phase is present at a } j \text{ bus} \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

$$\zeta(j) = |v(\bar{f},j) - v(f,j)| \quad (43)$$

- The general model for balanced and unbalanced systems is represented by (18)—(42).

$$\min \sum_{j\in N} x(j) \quad (18)$$

$$\max \sum_{i\in E} y(i) \quad (19)$$

s.t.: (20)

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{AT}(i,j)t^k(j) \geq t^A(i) \quad (21)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{BT}(i,j)t^k(j) \geq t^B(i) \quad (22)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{CT}(i,j)t^k(j) \geq t^C(i) \quad (23)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{AB}(i,j)t^k(j) \geq t^A(i)t^B(i) \quad (24)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{BC}(i,j)t^k(j) \geq t^B(i)t^C(i) \quad (25)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{AC}(i,j)t^k(j) \geq t^A(i)t^C(i) \quad (26)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{ABT}(i,j)t^k(j) \geq t^A(i)t^B(i) \quad (27)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{BCT}(i,j)t^k(j) \geq t^B(i)t^C(i) \quad (28)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{ACT}(i,j)t^k(j) \geq t^A(i)t^C(i) \quad (29)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} om^k_{ABC}(i,j)t^k(j) \geq t^A(i)t^B(i)t^C(i) \quad (30)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{AT}(i,\bar{i},j)t^k(j) \geq y(i)t^A(i)t^A(\bar{i}) \quad (31)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{BT}(i,\bar{i},j)t^k(j) \geq y(i)t^B(i)t^B(\bar{i}) \quad (32)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{CT}(i,\bar{i},j)t^k(j) \geq y(i)t^C(i)t^C(\bar{i}) \quad (33)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{AB}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in A,B} t^k(i)t^k(\bar{i}) \quad (34)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{BC}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in B,C} t^k(i)t^k(\bar{i}) \quad (35)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{AC}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in A,C} t^k(i)t^k(\bar{i}) \quad (36)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{ABT}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in A,B} t^k(i)t^k(\bar{i}) \quad (37)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{BCT}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in B,C} t^k(i)t^k(\bar{i}) \quad (38)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{ACT}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in A,C} t^k(i)t^k(\bar{i}) \quad (39)$$

$$\sum_{j\in N} x(j) \sum_{k\in F} \sigma^k_{ABC}(i,\bar{i},j)t^k(j) \geq y(i) \prod_{k\in F} t^k(i)t^k(\bar{i}) \quad (40)$$

$$x(j) \in \{0,1\} \quad (41)$$

$$y(i) \in \{0,1\} \quad (42)$$

• Methodology

• Step 4: Solve the BILP model

- The PQM's allocation problem has multiple nondominated solutions related to a single Pareto front's point. In other words, the PQMs can be combined in several ways reaching the same identification of faults with the exact number of PQMs.

- The multi-objective model was solved through the **Algorithm for Bicriteria Discrete Optimization (ABCDO)**. However, **ABCDO returns only one solution** for each Pareto front's point.

- Therefore, we explore the **Nondominated Sorting Genetic Algorithm II (NSGA-II**) population characteristic to find other solutions. The obtained solutions from ABCDO were included in the initial population of an NSGA-II.

Methodology

Step 5: PQMs positions

- This step chooses one Pareto point and processes all related solutions found by the NSGA-II.
- It identifies **groups of buses** and **combines one bus of each group to form a solution**.
- This step also evaluates the **second objective function (maximising the number of identified faults)** for all combinations to ensure dominance level.
- If one combination does not belong to the Pareto front, this step excludes it from the final set of solutions.

• Results and discussion

• CIGRÉ 15-bus test system

- Since we considered no-load conditions in fault simulations, the results show four-fault types **(187 solid faults x 4 = 748 faults)**.
- **First scenario**: DG disconnected
- **Second scenario**: DG connected
- The results suggest that the DG presence reduces the identification capability of monitoring programs.

TABLE II
ABCDO RESULTS CONSIDERING SOLID FAULTS AND $\tau = 0.6$ P.U.

Instance	First scenario: Pareto point $(o1, o2)$	First scenario: PQMs positions	Second scenario: Pareto point $(o1, o2)$	Second scenario: PQMs positions
AG	(2, 187)	**11, 14**	(2, 169)	**11, 14**
			(3, 178)	**3, 11, 14**
			(4, 179)	**3, 4, 11, 14**
BC	(2, 134)	**11, 14**	(2, 118)	**11, 14**
	(3, 167)	**1, 11, 14**	(3, 151)	**11, 13, 14**
	(4, 169)	**1, 2, 11, 14**	(4, 153)	**2, 11, 13, 14**
	(5, 171)	**2, 5, 10, 13, 15**	(5, 155)	**2, 11, 12, 13, 15**
BCG	(2, 187)	**12, 14**	(2, 173)	**11, 14**
			(3, 177)	**6, 11, 14**
ABC	(2, 154)	**11, 14**	(2, 139)	**11, 14**
	(3, 187)	**11, 13, 15**	(3, 172)	**1, 11, 14**
			(4, 177)	**6, 11, 13, 15**
All types together			(2, 599)	**11, 14**
	(2, 662)	**10, 14**	(3, 665)	**1, 11, 14**
	(3, 728)	**1, 10, 14**	(4, 680)	**1, 6, 11, 14**
	(4, 730)	**1, 2, 10, 14**	(5, 684)	**1, 2, 6, 11, 14**
	(5, 732)	**2, 7, 12, 13, 15**	(6, 686)	**1, 3, 6, 11, 12, 14**
			(7, 688)	**2, 3, 6, 11, 12, 13, 15**

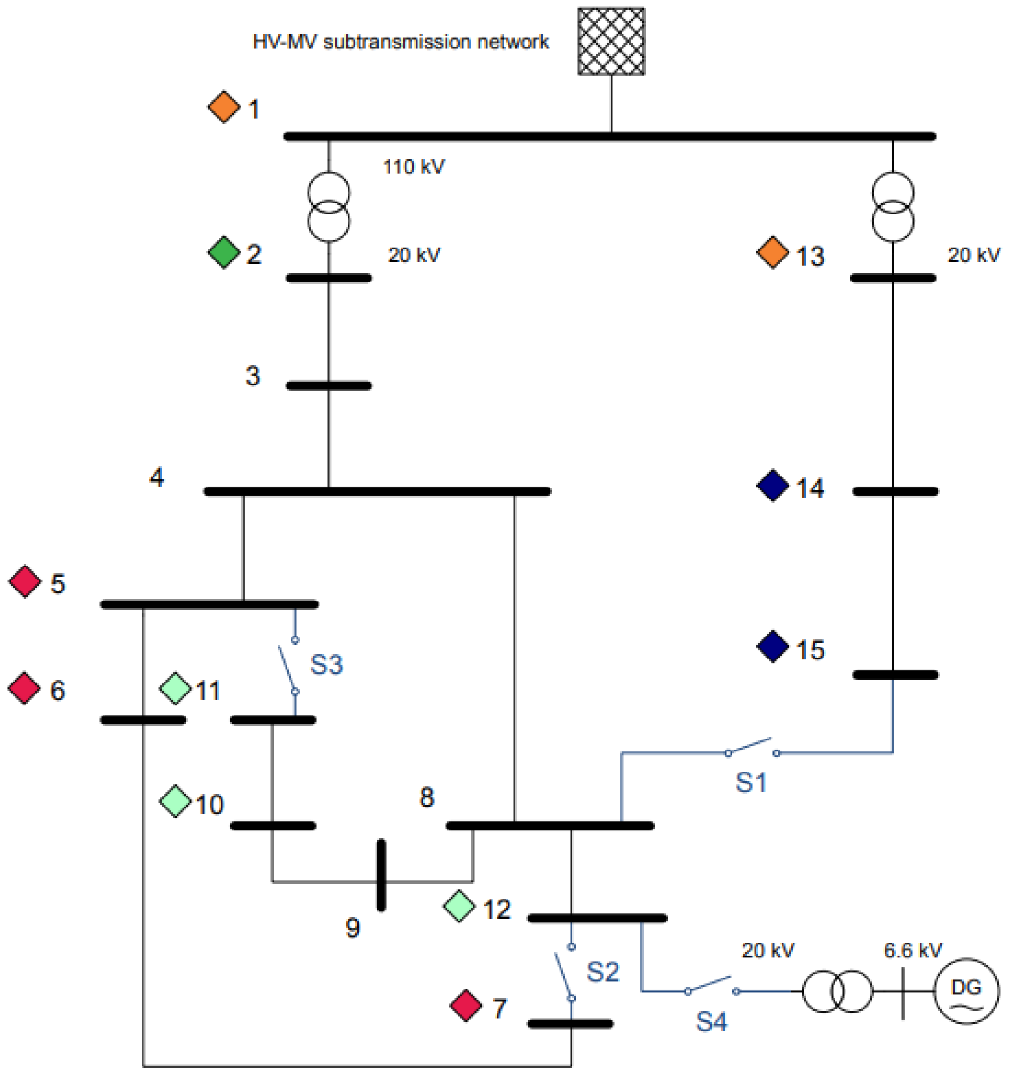
• Results and discussion

• CIGRÉ 15-bus test system

- This figure illustrates all NSGA-II solutions considering the connected distributed generator and all fault types.

- The colors divide these buses into **five groups** and choosing one bus from each group always leads to a solution that belongs to the Pareto front.

- Solution **{2, 7, 12, 13, 15}** found by ABCDO can be composed through these five groups.



• Results and discussion

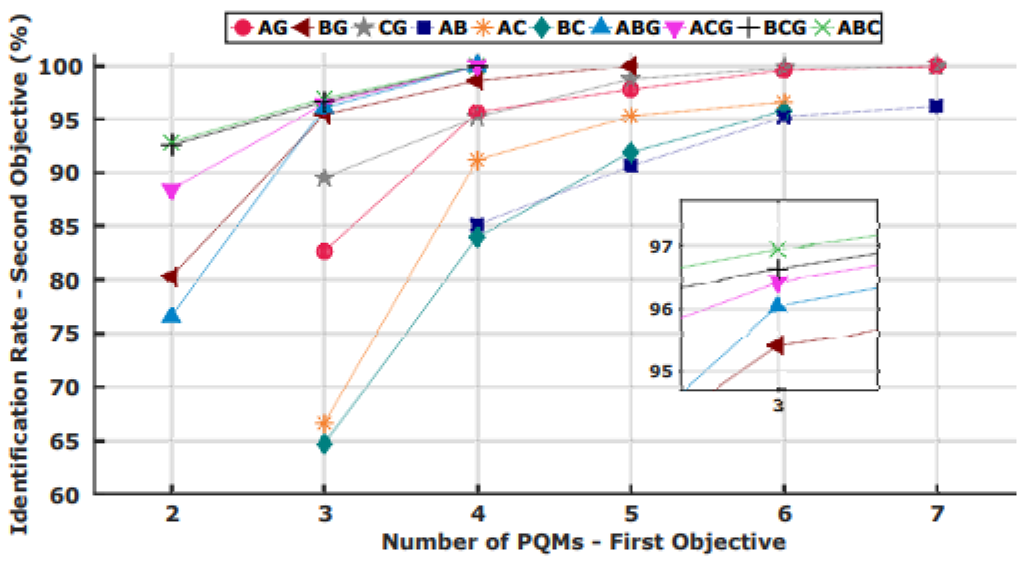
• CIGRÉ 15-bus test system

- Solution **{11, 14}** suits all instances and has the lowest cost.
- Solution **{2, 3, 6, 11, 12, 13, 14}** reaches the maximum benefit.

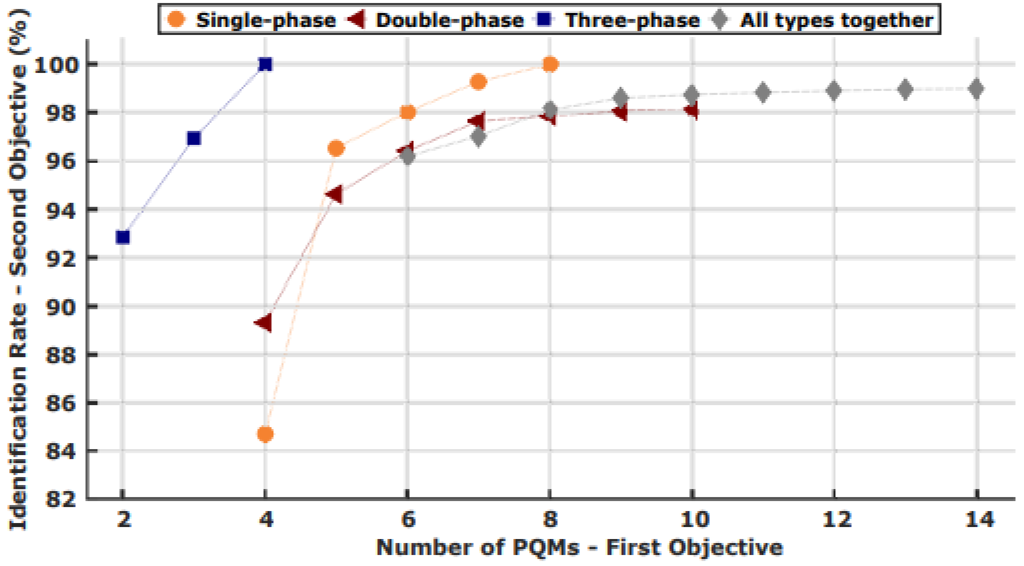
TABLE III
ALTERNATIVE SOLUTIONS OBTAINED BY NSGA-II FOR EACH POINT IN THE OBJECTIVE SPACE CONSIDERING THE SECOND SCENARIO

Instance	Pareto point ($o1$, $o2$)	Optimal solutions
AG	(2, 169)	**{11, 14}**, {11, 15}
	(3, 178)	**{3, 11, 14}**, {3, 11, 15}
	(4, 179)	**{3, 4, 11, 14}**, {3, 4, 11, 15}, {3, 5, 11, 14}, {3, 5, 11, 15}, {3, 6, 11, 14}, {3, 6, 11, 15}, {3, 7, 11, 14}, {3, 7, 11, 15}
BC	(2, 118)	**{11, 14}**, {12, 14}
	(3, 151)	{1, 11, 14}, {1, 11, 15}, {1, 12, 14}, {1, 12, 15}, **{11, 13, 14}**, {11, 13, 15}, {12, 13, 14}, {12, 13, 15}
	(4, 153)	{1, 2, 11, 14}, {1, 2, 11, 15}, {1, 2, 12, 14}, {1, 2, 12, 15}, {1, 11, 12, 14}, {1, 11, 12, 15}, **{2, 11, 13, 14}**, {2, 11, 13, 15}, {2, 12, 13, 14}, {2, 12, 13, 15}, {11, 12, 13, 14}, {11, 12, 13, 15}
	(5, 155)	{1, 2, 11, 12, 14}, {1, 2, 11, 12, 15}, {2, 11, 12, 13, 14}, **{2, 11, 12, 13, 15}**
BCG	(2, 173)	**{11, 14}**, {11, 15}
	(3, 177)	**{6, 11, 14}**, {6, 11, 15}
ABC	(2, 139)	**{11, 14}**
	(3, 172)	**{1, 11, 14}**, {1, 11, 15}, {11, 13, 14}, {11, 13, 15}
	(4, 177)	{1, 6, 11, 14}, {1, 6, 11, 15}, {6, 11, 13, 14}, **{6, 11, 13, 15}**
All types together	(2, 599)	**{11, 14}**
	(3, 665)	**{1, 11, 14}**, {1, 11, 15}, {11, 13, 14}, {11, 13, 15}
	(4, 680)	**{1, 6, 11, 14}**, {1, 6, 11, 15}, {6, 11, 13, 14}, {6, 11, 13, 15}
	(5, 684)	**{1, 2, 6, 11, 14}**, {1, 2, 6, 11, 15}, {1, 3, 6, 11, 14}, {1, 3, 6, 11, 15}, {2, 6, 11, 13, 14}, {2, 6, 11, 13, 15}, {3, 6, 11, 13, 14}, {3, 6, 11, 13, 15}
	(6, 686)	{1, 2, 3, 6, 11, 14}, {1, 2, 3, 6, 11, 15}, {1, 2, 6, 11, 12, 14}, {1, 2, 6, 11, 12, 15}, **{1, 3, 6, 11, 12, 14}**, {1, 3, 6, 11, 12, 15}, {2, 3, 6, 11, 13, 14}, {2, 3, 6, 11, 13, 15}, {2, 6, 11, 12, 13, 14}, {2, 6, 11, 12, 13, 15}, {3, 6, 11, 12, 13, 14}, {3, 6, 11, 12, 13, 15}
	(7, 688)	{1, 2, 3, 6, 11, 12, 14}, {1, 2, 3, 6, 11, 12, 15}, {2, 3, 6, 11, 12, 13, 14}, **{2, 3, 6, 11, 12, 13, 15}**

- **Results and discussion**
- **IEEE 123-bus test system**



Pareto front obtained for all fault types solved individually to IEEE 123-bus.

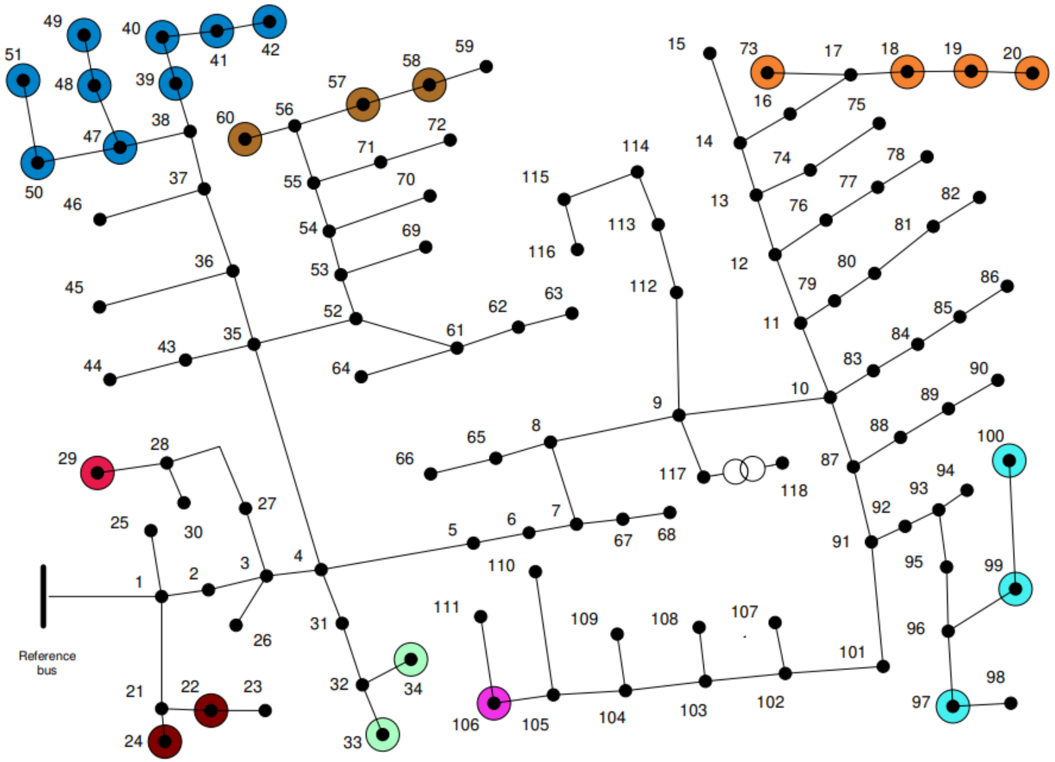


The Pareto front obtained for all fault types solved together to IEEE 123-bus.

• Results and discussion

• IEEE 123-bus test system

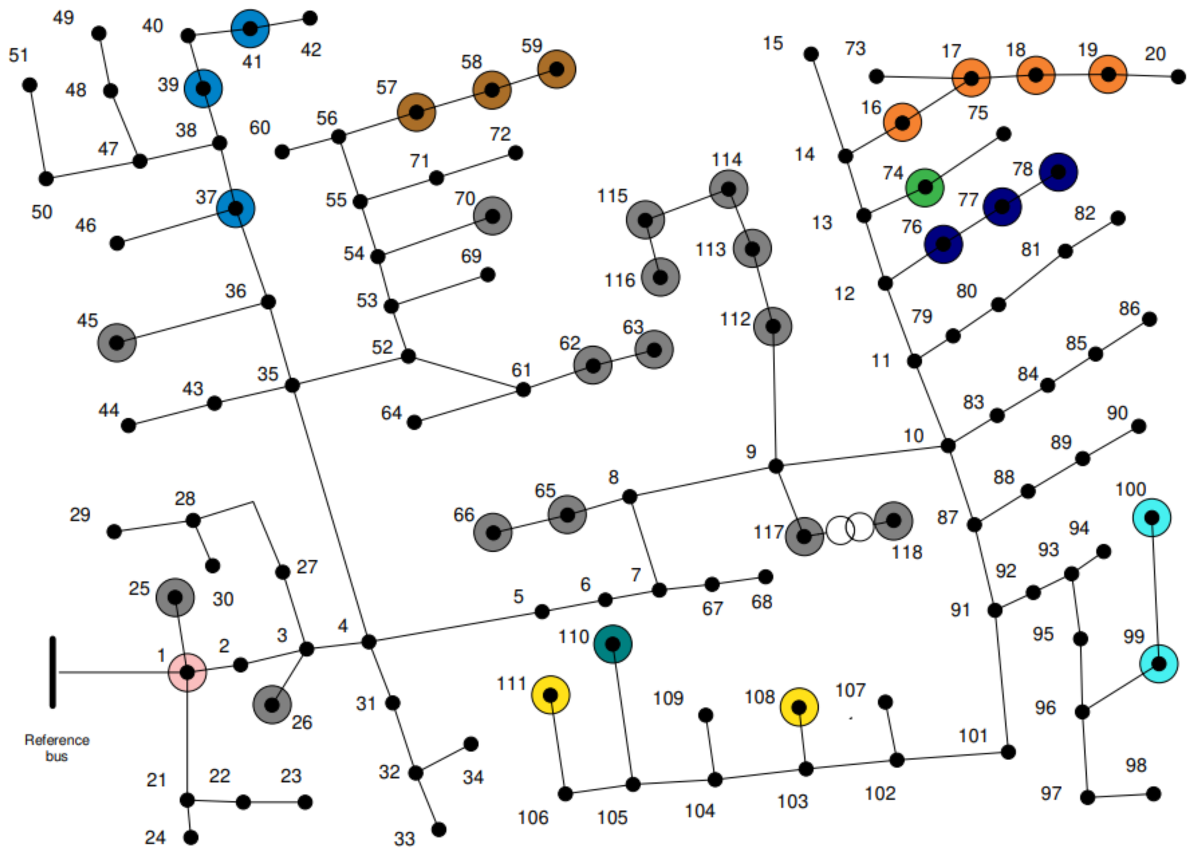
- The figure has **eight different colors**.
- Then each solution has eight PQMs.
- Any combination made with buses within these eight sets is a solution.



Set of PQMs for single-phase to ground faults.

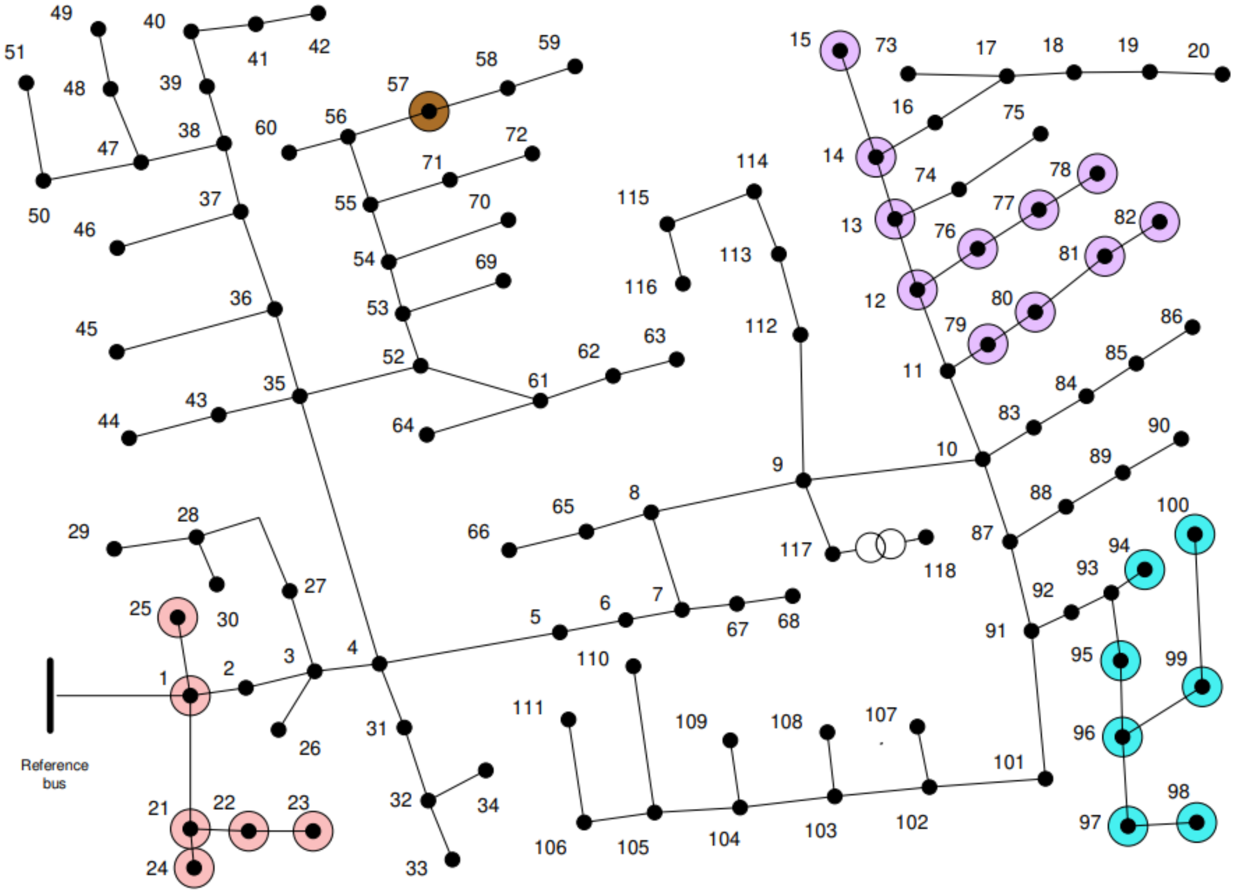
• Results and discussion

• IEEE 123-bus test system



Set of PQMs for double-phase faults (with and without ground connection).

- # Results and discussion
- ## IEEE 123-bus test system



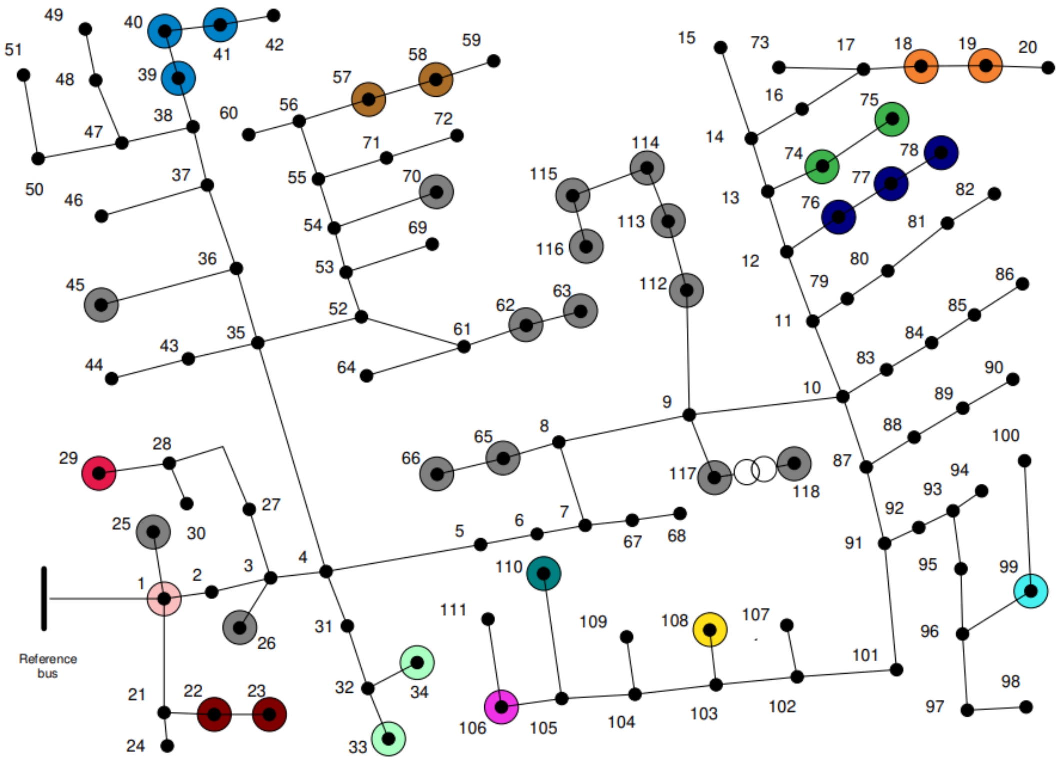
Set of PQMs for three-phase faults.

• Results and discussion

• IEEE 123-bus test system

- These solutions correspond to the Pareto point of **14 PQMs** and **99% of identification rate**.

- But it is worth mentioning that an **identification rate above 96%** was obtained with **only six PQMs**.



Set of PQMs for all types of faults.

• Results and discussion

• EPRI’s Ckt5 2998-bus test system

- We simulated three-phase faults at all buses of the **EPRI's Ckt5 2998-bus system** to determine if the proposed methodology applies to large power systems.

- We ran **pre-fault conditions in the EPRI’s system** to investigate the method’s practical application.

- The results presented three Pareto points. And with **four PQM** it was obtained a **68.75% identification rate**.

• Conclusions

- **Allocation method**: based only on the **root mean square voltages (Vrms)** measured at the buses.
- **The method considered** the **unbalanced nature of PDS** (selecting the appropriate method for short-circuits simulations; adding **topology** constants in the BILP model; and suggesting a **sequence of the reference phase selection**).
- **This paper investigated** the impacts of the connection/disconnection of a DG on the monitoring system performance. It was observed a **slight reduction in the monitoring set's identification capability after the DG connection**. These results are essential since utilities cannot predict low power DG connections.
- **The fault location in PDS remains an unsolved problem,** this paper contributes with a method that presents solutions with a significant reduction of multiple estimations.

Thank you!

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