A unified adaptive scheme for fault location and relay coordination in Smart Grids

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***Abstract*—This paper presents an adaptive protection scheme for distribution networks with distributed generation. The proposed system offers the novelty of being able to both locate the zone in which the fault has occurred and adapt the setting parameters of the relays involved in the process for each network condition. The unified adaptive system can be applied for fault detection in both the main feeder and lateral branches, taking into account the variable conditions of the distributed power generation and power demand. The setting of the relays' parameters responsible for the coordination of the zone protection is done by optimizing three degrees of freedom using mixed-integer nonlinear optimization techniques. The proposed adaptive protection scheme is validated in a standard distribution test feeder to prove its capability to locate faults in both main and lateral branches and optimize the performance of the involved relays under variable generation conditions, different fault types and different fault locations. The adaptive protection scheme reduces relay operating time significantly compared to classical and linear relay techniques.**

Keywords— adaptive protection, smart grids, distributed generation, photovoltaics, IEC 61850.

I. INTRODUCTION

Until a few decades ago, traditional protection schemes of distribution networks were mainly based on two aspects associated with its passive characteristic: unidirectional power flow from central power plants to the consumer and fixed settings of the protection units [1].

Nowadays, the connection of renewable energy sources at distribution networks affect both the reliability and sensitivity of power protection schemes due to the possibility of bidirectional power flows, which entails protection selectivity problems [2]. Moreover, distribution generation (DG) leads to protection sensitivity problems [3, 4-8] due to the variation of short-circuit currents seen by relays under high DG penetration levels.

As a result, traditional protection schemes in distribution networks with DG fail in most cases due to a lack of coordination, untimely tripping and operation failure [9, 10-11], as well as difficulties in locating and clearing the faults [12-16].

Recently, new adaptive protection schemes have been applied to distribution networks. However, the majority of the adaptive protection schemes have two limitations: (1) they focus only on relay coordination, leaving aside the problem of fault location, and (2) a static load and generation scenario is used to determine relay settings parameters. Furthermore, none of the approaches above consider the problem of fault detection in lateral branches that is a problem of difficult resolution because of the phenomena of multiple fault location for a single fault [17].

Traditionally, fault location has been mainly focused in transmission power networks [18-19]. However, fault location techniques applied in transmission networks fail to provide an exact fault location in distribution networks due to the non-homogenous lines' characteristics, the presence of laterals branches, dynamic behaviour of customers' demand, as well as the incorporation of DG units [20]. For that issue, it is necessary to develop new fault location methods for distribution networks with the presence of DG units.

The main contribution of this paper includes the development of a unified protection system capable of detecting the faulted zone, both in the main feeder and in the laterals, and the optimization of the adjustment parameters of the protections devices (IEDs) in charge of protecting the faulted section, taking into account the variable conditions of the network (topology, demand and generation) at the fault instant of time. Note that the problem of fault detection for lateral lines remains unsolved by the scientific community [17].

II. ADAPTIVE PROTECTION

Although adaptive protections have been applied to power networks during the last decades [21-22], there are still important challenges to overcome, such as the adaptation of protection device settings according to variable conditions of demand or generation production, changes in the grid topology, variations in the number of DG units connected to the grid, etc.

An adaptive protection scheme (APS) with the ability to locate the faulted section and optimally coordinate the relay settings parameters of the affected section is described in the present paper. The three main elements involved in the protection scheme are as follows:

1) **APS-SAU***:* is the unit responsible for controlling the operation of the protection system and it is placed at the secondary substation of the distribution network.

*2) **APS-FL***: is the device responsible for the fault location once the fault has been detected by the measurement units.

*3) **APS-OARA***: is the device in charge of optimally coordinate the IEDs of the faulted section.

APS-SAU is linked to the two protection blocks: firstly to APS-FL in order to locate the fault section, and secondly to APS-OARA to coordinate the IEDs of the affected section optimally. The communication between the APS-SAU and the other units of the protection scheme can be done according to IEC-61850 [23].

Moreover, both APS blocks (APS-FL and APS-OARA) communicate with the following elements:

- Intelligent Electronic Devices (IEDs) for protection and monitoring issues of electrical power networks. The IEDs receive their optimal settings (α, n, time-dial setting (TDS)) from the APS-OARA.
- Merging Units (MUs) that are installed at the secondary substation and the DG sources. They receive measurement requests from the APS-FL and send to the APS-FL the requested measurements registered at the DG connection point as well as the measurements at the substation.

The operating scheme of the APS consists of three stages:

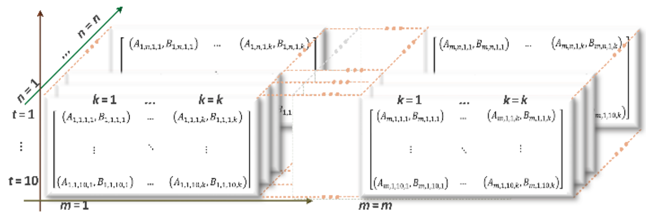
- offline database (BBDD) creation;
- fault detection (APS-FL); and
- IEDs coordination in the faulted section (APS-OARA).

A. Offline Database (BBDD) Creation

The offline database, BBDD (Fig.1), is located in the APS-SAU where the following information is stored:

- Positions of breakers/switches: When a fault is detected, the APS-SAU updates the status (open or closed) of the network's breaker/switches in the BBDD.
- Offline fault current contribution from each one of the generation sources ($I_{cc\_offline\_g\_tcdz}$). These values of short-circuit currents are previously calculated by short-circuit analysis in an offline stage, considering different system topologies ("t"), different types of faults ("c"), different DG units ("d") and different fault zones ("z"). The fault current contribution from each one of the generation units and from the grid are stored in tabulated form in the A_{tcdz} element of the offline BBDD.
- For each of the protection zones, identifiers of the primary and backup IEDs for the protection zone (r_{ptcdz}, r_{btcdz}). The selection of the IEDs pair depends on the network topology "t" and the fault location "z". The pair of IEDs to coordinate is saved in the B_{tcdz} element of the offline database.

It is important to point out that a radial distribution network is analysed in this work. In these radial networks faults in the main feeder are exclusively detected by the Fault locator without any confusion as maximum and minimum currents are compared in the extreme nodes. Faults at the lateral areas are normally solved by fuses.



$A_{m,n,t,k} = I_{cc_{p_{m,n,t,k}}}, I_{cc_{b_{m,n,t,k}}}$ $B_{m,n,t,k} = r_{p_{m,n,t,k}}, r_{b_{m,n,t,k}}$

Fig. 1. Structure of the Offline Database (BBDD).

B. Fault Detection (APS-FL)

The fault locator proposed in this work focuses on a fault location procedure that uses multi-terminal signals similar to that used in [1]. The steps involved to determine the location of the faulted section are described below.

- **Step 1:** Fault detection and fault type evaluation. Fault detection is achieved by the IED located at the transformer substation, which communicates with the APS-SAU. If the current through this IED exceeds the current threshold, there is a fault in the network. IEDs' phase measurements allow determination of the type of fault ("c") (single-line to ground fault, line-to-line fault or three-phase fault). The APS-SAU sends both an activation signal and the current per phase measurements to the APS-FL.
- **Step 2:** Reading of the online current contribution from the generation units, $I_{cc\_online,g}$. The APS-FL requests to each one of the MUs the DG's current measurement ($I_{cc\_online\_g\_tcdz}$) and the grid current measurement ($I_{cc\_online\_grid\_tcdz}$). For this communication, the standard IEC 61850 is used.
- **Step 3:** Calculation of the short-circuit current, I_{cc}. Once the phase currents measurements are available, the online short-circuit current, I_{cc}, is calculated as the sum of the contribution from the different sources to the fault (1), [1],

$$I_{cc} = \sum_{i=1}^{g} I_{cc\_online\_g\_tcdz} + I_{cc\_online\_grid\_tcdz} \quad (1)$$

- **Step 4:** Selection of sub-table of the BBDD. The APS-FL selects from the BBDD the sub-table associated to the current topology ("t") that contains the offline short-circuit currents from the DG sources and from the grid corresponding to the type of fault detected ("c") and to the number of DG units in operation ("d").
- **Step 5:** Detection of the faulted zone (Fig. 2). A zone "z" of the system is identified as the set of line sections included between two consecutive relays: "from" and "to". Since the protection zones are overlapped, the relay "to" of a zone "z" will, in turn, be the relay "from" of zone "z + 1". The detection process of the faulted zone is defined in the following way:
  - From the BBDD sub-table, the offline fault currents' contribution by each source (network, DGs) at the "from" nodes of each zone ($I_{cc\_offline\_g\_tcd\_from\_z,}$, $I_{cc\_offline\_g\_tcd\_from\_z+1}$) are extracted.
  - In the event of a fault in a zone "z", the measured (online) current supplied by each source 'g' (DG, network) ($I_{cc\_online\_g\_tcd}$) must lie between the offline

fault current values occurring at the extreme nodes of the zone ($I_{cc\_offline\_g\_tcd\_from\_z}$, $I_{cc\_offline\_g\_tcd\_from\_z+1}$) [1]. If the measurement of the short-circuit current is found to be between the tabulated values at each end of the zone "z", then it is concluded that the fault is located inside the zone "z". Otherwise, the above procedure is repeated to the adjacent zone until the identification of the faulted zone for each one of the sources 'g' is found.

- Once the faulted zone has been identified, the APS-FL sends a fault location "*end signal*" to the APS-SAU.

- **Step 6.** In this step, the APS-FL selects the primary ($r_{p\text{-}tcdz}$) and backup ($r_{b\text{-}tcdz}$) relay pairs from the offline BBDD that need to be coordinated considering the fault zone "z", the fault type "c", the current topology "t" and the information of DG units in operation "d".

The APS-FL sends an activation signal to the APS- OARA together with the relay pair to be coordinated via GOOSE messages.

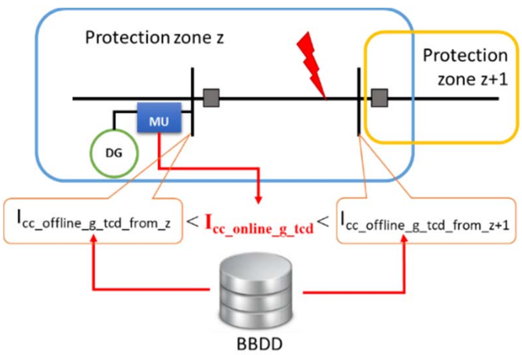


Fig. 2. APS-FL, Step 5: detection of faulted zone.

The communication between the different elements associated with the location of the faulted section using GOOSE messages is shown in Fig. 3.a. It has to be noted that he fault location elapsed time implemented in the algorithm is lower than 450 ms which is the maximum fault clearing time set by some Spanish utilities.

C. *Relay Coordination of the Faulted Zone (APS-OARA)*

The APS-OARA receives an activation signal from the APS-FL together with the pair of relays to coordinate ($r_{p\text{-}tcdz}$, $r_{b\text{-}tcdz}$) and requests the currents' measurements from each of the relays. In this step, the APS-OARA selects the corresponding I_{pickup} currents from the BBDD. The communication via GOOSE messages between the different elements involved in the coordination of the relays of the faulted zone is shown in Fig. 3.b.

The APS-OARA computes the optimal settings of each relay. The optimization problem proposed for the adaptive coordination of relays is a nonlinear multivariable problem since the tripping time, T_r, depends on α, n and TDS (2). In this paper, the setting parameters of relay (α, n and TDS) is based on optimization techniques using three degrees of freedom in the coordination process.

$$T_{r,tczd} = TDS_{r\_tczd} * \frac{\alpha_{r\_tczd}}{\left(\frac{I_{sc_{r\_tczd}}}{I_{pickup}}\right)^{n_{r\_tczd}} - 1} \quad (2)$$

The objective function is formulated as (3):

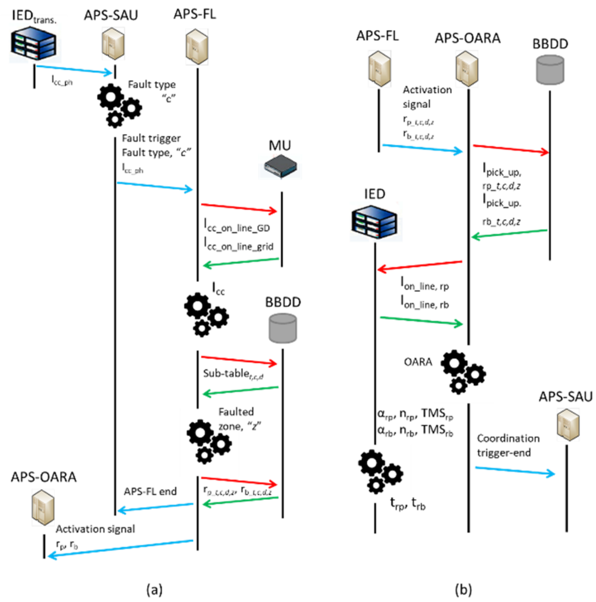


Fig. 3. APS exchange information: (a) fault location, (b) relay coordination.

$$Min\ T_{operation} = W_i \sum_{i=1}^{m} T_{rp\_tcdz} + W_j \sum_{j=1}^{n} \Delta T_{rp,rb\_tcdz} \quad (3)$$

And the following constraints are considered:

$$CTI_{rp,rb_{min}} \leq CTI_{rp,rb} \quad (4)$$

$$t_{r,max} \leq t_{r\_tcdz} \leq t_{r,min} \quad (5)$$

$$TDS_{r,max} \leq TDS_{r\_tcdz} \leq TDS_{r,min} \quad (6)$$

$$PS_{r,max} \leq PS_r \leq PS_{r,min} \quad (7)$$

$$\alpha_{r,min} \leq \alpha_{r\_tcn} \leq \alpha_{r,max} \quad (8)$$

$$n_{r,min} \leq n_{r\_tcn} \leq n_{r,max} \quad (9)$$

Where CTI is the coordination time interval between primary and backup relays, t is the operation time, and PS is the plug setting multiplier.

To solve the convex problem, a mixed-integer nonlinear optimization method (MINLP) is used that is based on the interior point method, in which both the objective function and the constraints are continuous, and its first derivative is also continuous.

After the execution of the APS-OARA, the optimal characteristic parameters are sent, via GOOSE messages, to the protection devices responsible for protecting the faulted zone (α_{rp}, n_{rp}, TDS_{rp}, α_{rb}, n_{rb}, TDS_{rb}). The process ends with the transmission of an "end signal" by the APS-OARA to the APS-SAU.

III. Case Study

The proposed adaptive protection scheme has been implemented in a distribution network based on the topology of the IEEE 34-Node Test Feeder [24], as illustrated in Fig. 4. The network consists of photovoltaic (PV) farms at nodes 20 and 22 as well as intelligent protection devices (IEDs) at nodes 1, 4, 8, 12, 14 and 16 of the main feeder and at node 26 of the lateral 5. The location of the IEDs subdivides the main feeder of the study system into 7 protection zones (Table I). The network data are available in [25].

The off-line database BBDD contains information about fault current contributions by the grid and from each DG unit considering 10 types of short-circuits at each zone of the network. The database has the following dimensions: 't=1' topologies; 'c=10' fault types; 'z=7' zones; and 'd=2' DG units (t × c × z ×d). This section shows the results obtained when applying the proposed APS scheme to the scenarios shown in Table II.

A. APS General Performance (APS-SAU)

In this section, the operation of the APS is analyzed, step by step, for scenario B which correspond to a three-phase fault at main line and one of the DG units is out of service (DG20). In this scenario the total demand of the network at the fault instant is 80% of the substation transformer capacity (9.88 MW), and there is a DG penetration level of 50% due to the PV generation at node 22 of 4.94 MW.

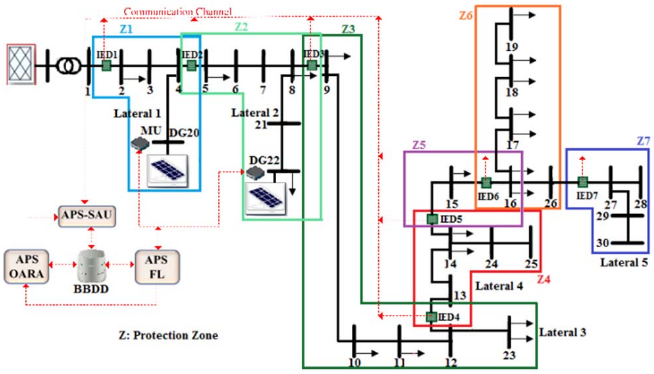


Fig. 4. Modified IEEE-34 test system

TABLE I. PROTECTION ZONES

Zone	Buses		Lateral		Primary relay	Backup relay
	from	*to*	*from*	*to*		
1	1	4	4	20	IED 1	-
2	4	8	8	22	IED 2	IED 1
3	8	12	12	23	IED 3	IED 2
4	12	14	14	25	IED 4	IED 3
5	14	16	16	26	IED 5	IED 4
6	16	19	-	-	IED 6	IED 5
7	-	-	27	30	IED 7	IED 6

TABLE II. SCENARIOS

Scenario	DG20	DG22	Fault		
			Type	*location*	*Line*
A	✓	-	Three-phase	Main line (zone 2)	6-7
B	-	✓			
C	✓	✓			
D	✓	-	Single-phase-to ground	Main line (zone 2)	6-7
F	✓	✓			
L	✓	✓		Lateral 5 (zone 7)	27-28

1) Location of the faulted section: APS-FL

Initially, the APS-SAU communicates first with the APS-FL to locate the faulted section. Consequently, the APS-FL executes the following steps:

- **Step 1: Fault detection**. In scenario B, the transformer's IED detects a three-phase fault with an overcurrent of 4187 A exceeding the tripping threshold of that unit set at 720.8 A. In this fault condition, the transformer's IED sends a trip signal to the APS-SAU, which collects information regarding the measurement of the three phase currents.
- **Step 2: Measurements of the three phase currents**. The APS-FL requests the current measurement from the DGs units and from the transformer's IED at the fault instant of time. In this scenario, the current measurement at the secondary substation is I_{grid}= 4183.2 A, and for the DG unit located at bus 22 is I_{DG22}=1902.9 A. In scenario B, the PV at node 20 does not supply current to the fault, I_{DG20}=0.0 A.
- **Step 3: Calculation of the short-circuit current.** The short-circuit current at the fault location is calculated according to (1), obtaining a value of I_{cc} =6044.1 A.
- **Step 4 Selection of the data sub-table of the BBDD.** In scenario B a three-phase fault is produced when DG_{20} is not injecting power. Consequently, the corresponding sub-table for scenario B is selected (only DG_{22} is in operation and a three-phase fault is produced) (Table III).
- **Step 5: Location of the faulted section**. At each zone, the offline fault currents at each node (Table III) are compared with the online current registered by the MUs (step 2). As can be seen in Table IV, the fault occurs in protection zone 2.

TABLE III. RELAY, GRID AND PV OFFLINE CURRENTS FOR SHORT-CIRCUITS IN THE MAIN FEEDER (SCENARIO B)

Fault		I_{cc} (A)	I_{grid} (A)	I_{DG22} (A)
Zone 1	*Max*	7555.9	5940.8	1955.2
	Min	6486.8	4695.4	1896
Zone 2	*Max*	6486.8	4695.4	1896
	Min	6009.2	4116.1	1795.6
Zone 3	*Max*	6009.2	4116.1	1795.6
	Min	3400.9	2311.1	1089.7
Zone 4	*Max*	3400.9	2311.1	1089.7
	Min	3118.1	2113.3	1001.3
Zone 5	*Max*	3118.1	2113.3	1001.3
	Min	2989.9	2023.8	961.3
Zone 6	*Max*	2989.9	2023.8	961.3
	Min	2527.2	1701.3	816.9
Zone 7	*Max*	2527.2	1701.3	816.9
	Min	1507.9	814.3	547.1

- **Step 6: Communication to the relays to coordinate.** In zone 2 (Table I), the relays responsible for protecting the network are IED2 and IED1, which are the primary and backup relays, respectively. The APS-FL sends that information to the APS-OARA via GOOSE messages.

2) Adaptive protection coordination

The APS-OARA executes the optimization algorithm (2)-(9) using the measured short-circuit currents seen by the relays to coordinate as well as their corresponding I_{pickup} currents (Table V), and the minimum and maximum thresholds values of the optimization variables [26]. Table V shows the primary and backup relay parameters α, n and TDS based on the optimization of the three degrees of freedom as detailed in section II. Taking into account the optimized parameters calculated by the APS-OARA, primary and backup relay operation times are 0.1s and 0.29s respectively.

TABLE IV. OFF_LINE AND ON_LINE FAULT CURRENTS FOR SCENARIO B

	Zone 2		
	$I_{offline\_max}$ (A)	I_{online} (A)	$I_{offline\_min}$ (A)
I_{grid}	4695.4	**4183.2**	4116.1
I_{DG22}	1896	**1902.9**	1795.6
I_{cc}	6486.8	**6086.1**	6009.2

TABLE V. RELAY PICK-UP CURRENTS AND APS-OARA PARAMETERS FOR SCENARIO B

	Primary Relay (IED2)	Backup relay (IED1)
Ipickup (A)	700	750
$\alpha_{APS-OARA}$	2	0.33
$n_{APS-OARA}$	0.14	0.33
$TDS_{APS-OARA}$	0.025	0.36

B. APS Performance under Different Fault Types and Fault Locations

In this section, the APS performance is shown for different fault types (three-phase and single-phase-to-ground) and different fault locations (main feeder, and lateral). Scenarios A, C, D and F of Table II consider two types of faults (three-phase and single-phase to ground) in the main feeder (zone 2) in two different operation conditions: when the two DG units are in operation and also when one of them is not injecting power. Scenario L correspond to faults in the lateral 5 which is included in zone 7. In this scenario the two DG units are in operation. In all cases, the DG penetration level is 50%.

Table VI shows the intervals of the offline currents for the studied scenarios along with the online currents registered by the DG units and the substation's IED. From this information, it can be verified that the APS-FL is able to detect the faulted zone of the system for single-phase to ground and three-phase faults (both in the main feeder), since the online currents lie within the interval defined by the offline currents.

Table VII shows the APS-FL results for different fault locations, (scenarios F and L). The offline and online short-circuit currents in Table VII demonstrate the ability of the APS-FL to locate faults in both the main and lateral lines in the presence of DG.

The results of the operating times obtained with the APS-OARA using the MINLP optimization algorithm is shown in Fig. 5 and its comparison with classical coordination techniques [2] and linear optimization methods [27] is shown in Table VIII. It can be noted that the APS-OARA is able to operate the primary relay, for all scenarios, with the minimum admissible value (t=0.1s). However, the classical coordination schemes [2] requires much more time, the operation time is 50-68.8% superior compared to APS-OARA. The same happens to the linear scheme [27], it delays its operation time between 37.5-63% compared with the APS-OARA. Referring to the backup relay, the APS-OARA takes between 0.28 s and 0.38s to operate the backup relay for the different scenarios. On the contrary, the classical schemes give an operation time of the backup relay up to 89.4% superior to the APS-OARA and similarly occurs to the linear techniques.

TABLE VI. OFF_LINE AND ON_LINE SHORT CIRCUIT CURRENTS FOR FAULTS IN THE MAIN FEEDER

		$I_{offline\_max}$ (A)	I_{online} (A)	$I_{offline\_min}$ (A)
Scenario A	I_{grid}	4412	**3738.7**	3673.3
	I_{DG20}	2209	**1864.1**	1849.3
	I_{DG22}	-	**-**	-
	I_{cc}	6613.1	**5602.8**	5515.2
Scenario C	I_{grid}	2232.8	**1939.5**	1861.8
	I_{DG20}	2284.4	**1957**	1920.2
	I_{DG22}	-	**-**	-
	I_{cc}	4550	**3896.5**	3805.2
Scenario D	I_{grid}	44414	**7470.3**	3676.8
	I_{DG20}	2206.8	**3751.7**	1845.8
	I_{DG22}	1788.7	**1846.7**	1888.7
	I_{cc}	8398.6	**1871.9**	7399.6
Scenario F	I_{grid}	2458.7	**2223.3**	2131.6
	I_{DG20}	2279.3	**1918.2**	1906.7
	I_{DG22}	1336.5	**1500.6**	1501
	I_{cc}	6037.7	**5642.1**	5533.5

TABLE VII. OFF_LINE AND ON_LINE SHORT-CIRCUIT CURRENT: SCENARIOS F AND L (DG PENETRATION LEVEL 50%).

		$I_{offline\_max}$ (A)	I_{online} (A)	$I_{offline\_min}$ (A)
Scenario F	I_{grid}	2458.7	**2223.3**	2131.6
	I_{DG20}	2279.3	**1918.2**	1906.7
	I_{DG22}	1336.5	**1500.6**	1501
	I_{cc}	6037.7	**5642.1**	5533.5
Scenario L	I_{grid}	1861.8	**741.5**	655
	I_{DG20}	1920.2	**617.4**	619
	I_{DG22}	491.6	**504.3**	-
	I_{cc}	3805.2	**1623.5**	1754.5

TABLE VIII. REDUCTION OF THE OPERATING TIME OF THE APS-OARA COMPARED WITH THE CLASSICAL AND LINEAR OPTIMIZATION SCHEMES.

Scenario	***Reduction of the operating time of the APS-OARA compared with other coordination schemes***			
	Classical scheme		***Linear optimization***	
	Backup relay	**Primary relay**	**Backup relay**	**Primary relay**
A	87.0 %	50.0 %	90.5 %	61.5 %
C	89.4 %	50.0 %	89.0 %	63.0 %
D	57.9 %	67.7 %	72.6 %	61.5 %
F	61.7 %	68.8 %	73.9 %	63.0 %
L	45.3 %	50.0 %	56.1 %	37.5 %

It can be seen in Table VIII that primary relay operation time is reduced in a 90% for three-phase faults in the main feeder compared with both, classic and linear programming, and up to a 73.9% in the presence of single-phase faults in the main feeder. Regarding single-phase faults in Lateral 5, the APS-OARA is able to reduce the primary relay operation time in a 45.3% and 56.1% compared with the classic and linear programming respectively.

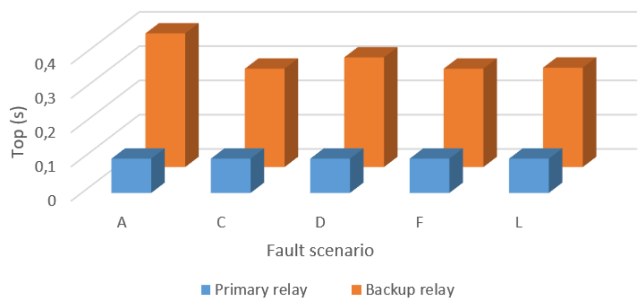


Fig. 5. APS-OARA operation time for different fault scenarios.

IV. Conclusions

A unified adaptive protection system that offers double functionality is proposed in this paper. Firstly, it is able to locate the faulted zone as soon as a fault is registered in the system. Secondly, it is able to optimize the settings parameters of the relays for each network situation. The performance of the APS has been tested for different DG penetration levels, different types of short circuit faults (single-phase to ground and three-phase) and different fault locations (faults in the main feeder and in the laterals). In all cases, the system is able to adapt, in real time, the performance parameters of the relays protecting the faulted line section depending on the operating conditions of the system at the fault's instant time

The proposed protection system has been applied to a distribution system in the presence of DG. The obtained results demonstrate the ability of the protection scheme to locate single-phase and three-phase short-circuit faults in both the main feeder and in the lateral lines of a distribution system with DG. Moreover, the optimization of the relays settings parameters improves the operation time of the primary and back up relays up to 68.8% and 89.4% comparing with linear programming, respectively.

The proposed scheme can be implemented in distribution systems using the communications standard IEC61850.

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