Application of µPMUs for fault location on LV networks

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Abstract*—In recent years, the electrical system has undergone numerous changes that have made it necessary to make electrical networks more intelligent. A clear example of this is the low voltage electrical system, which with the inclusion of distributed generation has made that the low voltage system have bidirectional power flows and therefore it is necessary to have real-time information on the status of the system. Because of this, it is necessary to have methods that, based on these measurements, can identify and locate low voltage faults quickly and efficiently. Until now it had not been thought of incorporating µPMUs into the low voltage system and therefore there are no methods for locating faults using µPMUs.The two methods have been implemented to locate faults based on state estimators. The main difference between both methods lies in the number of PMUs used. The first method uses a number of PMUs that allows to have a total system observability, this allows to perform several estimates in parallel. The selection of the line where the fault has occurred is based on choosing the line with the lowest weighted measurement residuals. The second method uses the minimum number of PMUs necessary to locate the faults, it works carrying out an iterative process of state estimators based on the different measurements of the PMU. This iterative process is carried out until the state estimator of the different measurements converge at the fault location. Both methods have been tested by simulating different faults in various points of a low voltage system with 14 buses obtained from SPEN. Each method has been able to locate the faults with very accurate results. The implementation of these methods in the low voltage electrical system could help to reduce some performance indicators from the DSOs as the CML and therefore increasing the benefits of the DSO and making customers more satisfied.

***Index Terms*—μPMU, State Estimation, Fault Detection, Linear Weighted Least Squares State Estimator**

I. INTRODUCTION

System reliability and resilience are major goals of the modernization and creation of a smarter grid. The distribution network in recent years has undergone certain changes that have changed its traditional mode of operation. Among the most prominent are the inclusion of renewable electricity generation sources, smart meters, distributed generation, among others. Many of these changes are influenced by concern for the environment and the aim is to reduce the damage that can be caused by electricity generation in the environment.

Historically, the low-voltage distribution network was designed for a one-way power flow, which consisted of the energy that came from the transformation center to the consumers. The inclusion of solar panels and other renewable generation sources such as cogeneration has made it necessary to monitor and control the low voltage grid.

There are numerous methods used for locating medium voltage faults, but regarding the low voltage grid, not many methods have been developed. These are due to the fact that the low voltage grid has certain differences with respect to the medium voltage network that makes more difficult to develop it. Some of the most notable are:

- System loads distributed unevenly.
- The system is usually unbalanced making it necessary to consider each phase separately.
- Until recently, limited number of measurements, making monitoring difficult.

The inclusion of methods to detect faults in LV is necessary, it will help to reduce the outages time, this is necessary because the power outages cause immersive amount of annual economic losses in every country, the cost of each outage increases with duration, making necessary to reduce fault duration as much as possible. Automated fault location systems have the potential to reduce outage time and costs to customers by allowing for fast and efficient deployment of repair crews. The main problems related to these outages is that they usually occur on the distribution system, where the cost of undergrounding or heavily instrumenting every feeder also becomes very high. An effective fault location system should be accurate enough to direct maintenance crews directly to the point of the fault and be cost effective such that significant investments are not required to enable the system.

Anyhow, the protection system has been developed for each part of the grid and it can be very complex and can differ according to its characteristics. A variety of devices, like breakers, relays, Remote Terminal Units (RTUs), Phasor Measurement Units (PMUs) etc. are deployed for the protection of the grid. The goal is the minimization of the CI (Customer Interruptions) and CML (Customer Minutes Lost), CI being the number of customers interrupted of the electricity provider when an outage occurs and CML being calculated with the product of CI and minutes of outage, of the least amount of costumers, when a fault occurs. The last part can be achieved with the correct cooperation of the protection devices [1].

Since, almost in their entirety, most of the changes of the electric system are taking place in the distribution network, that is the field with the most challenges and opportunities for innovation as well. The most important parts in a distribution grid are the power lines, that can be overhead or underground, the power transformers regulating the voltage level, the bus bars and the various protection devices [1].

Automatic fault location on the distribution system is an increasing necessity for a resilient grid with fast service restoration after an outage. Motivated by the development of low cost synchronized voltage phasor measurement units (PMUs) for the distribution system, the PMU data stream that can be used for a variety of applications, making it easier to justify the investment in fault location. The accuracy of existing automatic fault location techniques are dependent either on dense deployments of line sensors or unrealistically accurate models of system loads.

II. EMPLOYED METHODS

In this project, 2 different methods have been used to detect and locate faults using μPMU. Each method uses a different technique and the number of PMUs used also differs. The second method, a total observability of the system is not available. This is because fewer μPMUs are used. These PMUs will be placed in the main Feeder and in the final bus of each line. Making it necessary for the state estimates made to correspond with the existing μPMU measurements. Therefore, an iterative process will be carried out to ensure that the state estimate in made by the different μPMUs of the system converge in the place where the fault has occurred.

A. 1º Method

In the first method, it is supposed that the state of the distribution system is observed by being able to measure the nodal voltages and injected current. This is done by the μPMU that is installed in all the work busses of the system. Making this assumption enable the use of linear state estimator (SE). The corresponding formulation for calculating the linear weighted least squares state estimator (LWLS-SE) for a standard distribution system is shown in this section. This method is based in the method developed in [6].

The state of a distribution system with n buses $x \in \mathbb{R}^N$ $(N = 3n * 2)$ can be expressed with the coordinates seen below:

$$x = \left[V_{1_{re}}^{a,b,c},\ .....,\ V_{n_{re}}^{a,b,c},\ V_{1_{im}}^{a,b,c},\ .....,\ V_{n_{im}}^{a,b,c}\right]^T \tag{1}$$

where:

$$V_{i_{re}}^{a,b,c} = [\ V_{i_{re}}^{a},\ \ V_{i_{re}}^{b},\ \ V_{i_{re}}^{c}\ ] \tag{2}$$

$$V_{i_{im}}^{a,b,c} = [\ V_{i_{im}}^{a},\ \ V_{i_{im}}^{b},\ \ V_{i_{im}}^{c}\ ] \tag{3}$$

Are respectively the three phases of the real and imaginary terms of the voltage phasor at a generic bus i of the system.

The number of buses equipped with μPMUs in the distribution system network is $\mathbb{C}$. The measurement consists of the real and imaginary parts of three phase-to-ground voltage phasors and three injected current phasors of the busses where the μPMU are installed. z is represented as:

$$z = [z_V, z_I]^T \tag{4}$$

where:

$$z_V = \Big[\ .....,\ V_{i_{re}}^{a,b,c}, ...,\ V_{i_{im}}^{a,b,c},\ .....\Big]^T \tag{5}$$

$$z_I = \Big[\ .....,\ I_{i_{re}}^{a,b,c}, ...,\ I_{i_{im}}^{a,b,c},\ .....\Big]^T \tag{6}$$

In which $i\ \in\ \mathbb{C}$.
To correlate the state variable of the system with the measurements it is necessary to fallow the following equation:

$$z = \mathbf{H}x + v \tag{7}$$

Where H is the measurement matrix and v is the noise of the measurement. Regarding v, it was stablished as a gaussian noise.

$$(v)\ \sim\ \ \mathcal{N}(0, \mathbf{R}) \tag{8}$$

Where $\mathbf{R}$ is a matrix that their terms are the accuracy of the measurement devices. The accuracy of the μPMU was obtained from several data sheet. The accuracy of the devices will be used as the noise that will be added to the measurements of the simulation. It is considered that the errors of the measurements have not a correlation between each other, because of this, the matrix will be stablished as:

$$\mathbf{R} = diag\left(\sigma_1^2, \dots,\ \sigma_i^2, \dots, \sigma_D^2\right) \tag{9}$$

The matrix H consist of 2 submatrix, $\mathbf{H}_V\ and\ \mathbf{H}_I$:

$$\mathbf{H} = \begin{bmatrix}\mathbf{H}_v \\ \mathbf{H}_I\end{bmatrix} \tag{10}$$

The submatrix $\mathbf{H}_v$ links the measurements of the voltage to the state variable. The submatrix terms are ones and zeros that are inferred from (7). The submatrix $\mathbf{H}_I$ links the measurements of the current with the state variable. The submatrix terms are elements of the admittances of the distribution system. The real and imaginary part of the currents of the system can be calculated by the fallowing expressions:

$$I_{i_{re}}^{P} = \sum_{h=1}^{n}\sum_{l=1}^{3}\left\lfloor G_{ih}^{pl}V_{h_{re}}^{l} - B_{ih}^{pl}V_{h_{im}}^{l}\right\rfloor \tag{11}$$

$$I_{i_{im}}^{P} = \sum_{h=1}^{n}\sum_{l=1}^{3}\left\lfloor B_{ih}^{pl}V_{h_{re}}^{l} + G_{ih}^{pl}V_{h_{im}}^{l}\right\rfloor \tag{12}$$

The indexes i and h correspond to the different busses of the system, p and l correspond to the phase indexes, B and G are respectively the imaginary and real terms of the elements of the admittances of the system. From these equations (11) and (12) it is possible to create the submatrix $\mathbf{H}_I$:

$$H_I = \begin{bmatrix}G_{ih}^{pl} & -B_{ih}^{pl} \\ B_{ih}^{pl} & G_{ih}^{pl}\end{bmatrix} \tag{13}$$

The LWLS-SE main objective is to minimize the following objective function:

$$J(x) = \sum_{i=1}^{D} \frac{\left(z_i - \sum_{h=1}^{N} H_{ix} x_h\right)^2}{R_{ii}} \tag{14}$$

To be able to calculate the state estimate with the measurements. First, it is necessary to calculate the Gain matrix:

$$\mathbf{G} = \mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} \tag{15}$$

With this matrix is it possible to calculate the estimated state:

$$\hat{x}_{LWLS} = \mathbf{G^{-1} H^T R^{-1}} z \tag{16}$$

The method used to detect and locate the faults is based on the following premises:

- A full knowledge of the admittances of the system, making the matrix H exact. Full knowledge of the admittances implies that the parameters of the line and the topology of the electrical system are fully known. The assumption of the knowledge of the parameters of the line is based on the fact that the lines of the distribution network have a standard configuration and the system operator should know the characteristics of the line of the system.
- Regarding the knowledge of topology of the system, it must be clarified that μPMUs can stream and record Boolean variables along with the synchrophasor data. These Boolean inputs may correspond, as is the case for the actual network described in this document, the state of the breakers connected to a supervised μPMU. Once the status of all breakers is collected by the phasor data concentrator, it is simple to determine the incidence matrix of the network and, therefore, its topology and the corresponding admission matrix used in the expression (13). This characteristic is another advantage of using μPMU for protection. This is due to the topology assessment can be easily rebuilt and tagged with limited time latencies.
- The accuracy of the measurement devices used for the noise added to the noise measurements in R is known. This is because the characteristics of the μPMUs employed are totally known thanks to the datasheets of the devices. The number of μPMU employed is equal to the number of busses: C=N. This is based on the fact that lately most of the literature has shown more interest in the employment of μPMU and their several applications, in this literature [4] [5], the issue of using μPMU at all the busses of the system has been discussed.
- Due to simulation characteristics, erroneous data measurements are not considered for the state estimation.
- It has been considered that during the faults an imaginary bus originates in the place where the fault occurs. This bus would be between 2 real buses and would absorb the fault current.

As it was explained before, the system has m-lines and n-buses. There is a μPMU installed in every bus. Considering the measurement set obtained from each μPMU, it is possible to calculate m-parallel state estimators, each state estimator uses a lightly different network topology from the others state estimator. The difference in the topology is based on the position of the fault, in that position the virtual bus will be allocated. The $j^{th} SE(j = 1, ..., m)$ considerate a virtual bus in the middle of the j^{th} line by using an state vector that contemplate the characteristics of the voltage of the virtual bus. The voltage of the virtual bus will be added to the state define in the equation (1).

$$\widetilde{x} = \left[V_{1_{re}}^{a,b,c},\ ..,\ V_{n_{re}}^{a,b,c},\ \ V_{n+1_{re}}^{a,b,c},\ V_{1_{im}}^{a,b,c},\ \ldots,\ V_{n_{im}}^{a,b,c},\ V_{n+1_{im}}^{a,b,c}\right]^T \tag{17}$$

The matrix H consist of 2 submatrix, $\mathbf{H}_V\ and\ \mathbf{H}_I$:

$$\widetilde{x}^j \approx\ x_{true}\ \forall\ j \tag{18}$$

$$\widetilde{x}^j \approx\ x_{true} \quad \widetilde{x}^j \neq\ x_{true} \qquad \forall\ j \neq\ f \tag{19}$$

$$WMR^j = \sum_{i=1}^{D} \frac{\left|z_i - \hat{z}_i^j\right|}{\sigma_{z_i}} \tag{20}$$

where $\hat{z}^j =\ \mathbf{H}^j \hat{x}^j$.

In the cases where there is no fault, the WMRs of all the state estimators are very close to each other. When there is a fault, the state estimators (except the one of the line where there is the fault) converge to a solution which value differs a lot from its true state, this solution is characterized by a high WMR. The state estimator that has the virtual bus placed in the faulted line has the lowest WMR. Thank to this, it is possible to identify the line affected by the fault.

To be able to detect a fault, it is necessary to compare the mean of the WMRs of all the state estimators, this is called WMR_{mean}. A fault is detected when the difference between the WMR_{mean} of two consecutive timesteps has an abrupt increase. To calculate the estimated fault currents, it is used the state returned by this SE with the admittance matrix. To be able to detect which fault type has happen, it is necessary to check the current in the phases of the virtual bus. The estimated current in the virtual bus that differs from zero are the ones affected by the fault.

The algorithm that summarizes the proposed method is given below. For every new data set coming from the μPMUs, it is necessary to compute the WMRs of the parallel state estimators and their WMR_{mean}. Checking if there has been a sudden increase in the WMR_{mean} of two consecutive timesteps, we are able to detect the presence of a fault. If a fault is detected, the index of the line with the minimum WMR identifies the faulted line. For last it is possible to estimate the fault type and fault current. In conclusion, the employment of this method allows to:

- Detect when a fault has occurred.
- To identify in which line the fault is.
- To identify the fault type
- To estimate the fault current

The algorithm used to detect the faults using PMU is:

```
function Fault Identification
for each time-step $k$ do
    compute $WMR_J \quad \forall j$
    if mean $(WMRs)|_k \gg$ mean$(WMRs)\,|_{k-1}$ then
        Fault $\leftarrow$ 1
        j = index of min(WMRs)
        Faulted Line $\leftarrow$ j
        $I^j = Y^j E^j$
        Fault Current $\leftarrow I^j_{virtual\ bus}$
        Fault Type $\leftarrow$ phases where Fault current $\neq 0$
    end if
```

B. 2º Method

The second method, a total observability of the system is not available. This is because fewer μPMUs are used. These μPMUs will be placed in the main feeder and in the final bus of each line. This method consists in that the state estimation is based on the measurements of each PMU, the state estimation based on each μPMU will converge in the place of the fault. Therefore, an iterative process will be carried out to ensure that the state estimation will converge in the place where the fault has occurred. This method is shown in the following section.

Regarding the state estimation of this method, there are many common elements with the previous method. The state of a distribution system with n buses $x \in \mathbb{R}^N$ $(N = 3n * 4)$ can be expressed with the coordinates seen below:

$$x = \left[V^{a,b,c}_{1_{re}},\ .....,\ V^{a,b,c}_{n_{re}},\ V^{a,b,c}_{1_{im}},\ .....,\ V^{a,b,c}_{n_{im}} \right]^T \tag{21}$$

where:

$$V^{a,b,c}_{i_{re}} = [\ V^a_{i_{re}},\ \ V^b_{i_{re}},\ \ V^c_{i_{re}}\ ] \tag{22}$$

$$V^{a,b,c}_{i_{im}} = [\ V^a_{i_{im}},\ \ V^b_{i_{im}},\ \ V^c_{i_{im}}\ ] \tag{23}$$

Are respectively the three phases of the real and imaginary terms of the voltage phasor at a generic bus i of the system. And:

$$I^{a,b,c}_{i_{re}} = [\ I^a_{i_{re}},\ \ I^b_{i_{re}},\ \ I^c_{i_{re}}\ ] \tag{24}$$

$$I^{a,b,c}_{i_{im}} = [\ I^a_{i_{im}},\ \ I^b_{i_{im}},\ \ I^c_{i_{im}}\ ] \tag{25}$$

Are respectively the three phases of the real and imaginary terms of the current phasor at a generic bus i of the system. The number of buses equipped with μPMUs in the distribution system network is $\mathbb{C}$. The measurement consists of the real and imaginary parts of three phase-to-ground voltage phasors and three injected current phasors of the busses where the μPMU are installed. z is represented as:

$$w = [w_V, w_I]^T \tag{26}$$

where:

$$w_V = \left[\ .....,\ V^{a,b,c}_{i_{re}}, ...,\ V^{a,b,c}_{i_{im}},\ .....\right]^T \tag{27}$$

$$w_I = \left[\ .....,\ I^{a,b,c}_{i_{re}}, ...,\ I^{a,b,c}_{i_{im}},\ .....\right]^T \tag{28}$$

In which $i \in \mathbb{C}$.
To correlate the state variable of the system with the measurements it is necessary to fallow the following equation:

$$w = \mathbf{Z}x + v \tag{29}$$

Where **Z** is the group of impedances and loads of the system connected to the buses and v is the noise of the measurement. Regarding v, it was stablished as a gaussian noise.

$$Z = [Z_line, Z_bus] \tag{30}$$

$$Z_{line} = [z_{line_1}, ..., z_{line_i}, ...z_{line_m}] \tag{31}$$

Where z_{line} is the impedance between two consecutive buses. Each z_{line} is composed by the real and imaginary parts of the impedance:

$$z_{line_i} = [z_{line_{i}re}, z_{line_{i}im}] \tag{32}$$

Regarding Z_{bus}:

$$Z_{bus} = \left[Z_{bus_1}{}^a, ...Z_{bus_i}{}^b, ..., Z_{bus_n}{}^c \right] \tag{33}$$

The elements of Z_{bus} are only connected to one of the phases in each bus, and they are also composed by a real and an imaginary part.

$$z_{bus} = [z_{busre}, z_{busim}] \tag{34}$$

Z links the measurements of the voltage and current to the state variables. They relation between the estimation and the measurement, use the next expression when they are in the same bus:

$$x^{a,b,c}_v = \ w^{a,b,c}_v \tag{35}$$

$$x^{a,b,c}_I = \ w^{a,b,c}_I \tag{36}$$

When the estimation is done in different buses of the measurements, the expressions used for the voltage are:

$$x^{a,b,c}_{v_{re\,i+1}} = \ w^{a,b,c}_{v_{re_i}} + w^{a,b,c}_{I_{re_i}} * z_{linere} + w^{a,b,c}_{I_{im_i}} * z_{lineim} \tag{37}$$

$$x^{a,b,c}_{v_{im\,i+1}} = \ w^{a,b,c}_{v_{im_i}} + w^{a,b,c}_{I_{im_i}} * z_{line_{i}re} + w^{a,b,c}_{I_{re_i}} * z_{line_{i}im} \tag{38}$$

Regarding the expressions used for the current when the estimation is done in different buses of the measurements.

$$x^{a,b,c}_{I_{re\,i+1}} = w^{a,b,c}_{I_{re_i}} + \frac{x^{a,b,c}_{v_{re\,i+1}} * z_{busre} + x^{a,b,c}_{v_{im\,i+1}} * z_{busim}}{z_{bus}{}^2_{re} + z_{bus}{}^2_{im}} \tag{39}$$

$$x^{a,b,c}_{im_{i+1}} = w^{a,b,c}_{I_{im_i}} + \frac{-x^{a,b,c}_{v_{re\,i+1}} * z_{busre} + x^{a,b,c}_{v_{im\,i+1}} * z_{busim}}{z_{bus}{}^2_{re} + z_{bus}{}^2_{im}} \tag{40}$$

Following the previous expressions, it is possible to estimate the state of the system buses.

The method used to detect and locate the faults is based on the following premises:

- A full knowledge of the admittances and loads of the system, making the calculations as exact as possible. Full knowledge of the admittances implies that the parameters of the line and the topology of the electrical system are fully known. The assumption of the knowledge of the parameters of the line is based on the fact that the lines of the distribution network have a standard configuration and the system operator should know the characteristics of the linee of the system.
- Regarding the knowledge of topology of the system, it must be clarified that μPMUs can stream and record Boolean variables along with the synchrophasor data. These Boolean inputs may correspond, as is the case for the actual network described in this document, the state of the breakers connected to a supervised μPMU.
- The accuracy of the measurement devices used for the noise added to the noise measurements in R is known. This is because the characteristics of the μPMUs employed are totally known thanks to the datasheets of the manufactures. The number of μPMU employed is equal to the number of system lines plus the main feeder. So for these system C=4. This method is based on using the less number of μPMU as possible and to be able to detect the fault.
- Due to simulation characteristics, erroneous data measurements are not considered for the state estimation.

As it was explained before, the system has m-lines and n-buses. There is a μPMU installed in the main feeder and in the end of the 3 lines of the system. Considering the measurement set obtained from each μPMU, it is possible to calculate the state estimators in all the busses of the system. The state estimation prefault is easy to calculate because all the data of the system are known. The main challenge is to be able to do the estate estimators post fault, because a priori the place where the fault occurred is not known. As the system is not fully observable with the number of μPMUs installed, it makes it necessary to first locate in which of the lines of the system the fault has occurred in order to estimate the values of the areas that are not affected by the fault.

In order to do this, voltage phase variations and voltage drops are analyzed in the PMU measurements. Depending on the greater variations between pre-fault and post-fault, it is possible to identify the area where the fault has occurred. Knowing this, the state estimates of the buses are calculated with the PMU measurements without fail. To later locate the branch affected by the fault, an iterative process is carried out. This process consists of using the PMU measurements of the main feeder (from now on called bus s) to estimate the state of all buses up to the end of the line (bus k).

While this estimate is being made, if the voltage of any bus (bus n) is less than that measured in bus k, the calculation of the system state estimate is stopped. Using the measurements of the K bus, the measurements up to the n bus are estimated. After this the n bus is considered the K bus and the process is repeated.If at one point $VE_{k-1} > V_k$ && $VE_k < V_k$. It means that the branch where the fault has occurred has been identified and therefore it is possible to perform the calculation to determine the distance where the fault has occurred.

Below is the block diagram that summarizes the operation of the second method. The first step is to detect the fault and, depending on the variations in the measurements, identify the area where the fault has occurred. After this, the iterative process of state estimation is carried out until it is possible to locate the branch where the fault has occurred. After this, it is estimated in which part of the branch the fault has occurred.

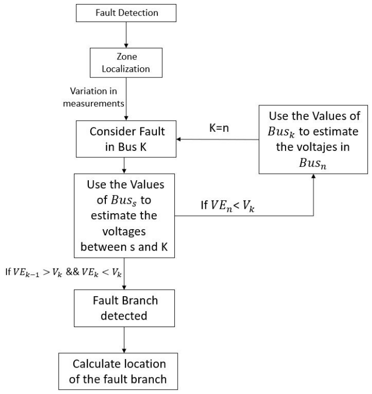

Fig. 1. Block diagram of the 2º method.

III. EVALUATION

The following low voltage system has been used in this project.

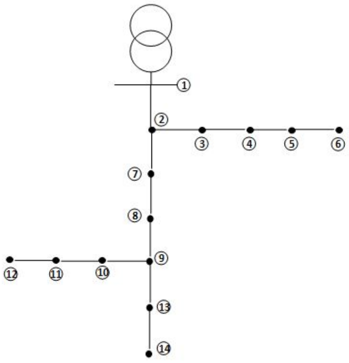

Fig. 2. Diagram of the simulated LV system.

As can be seen in the previous figure, the system has 14 nodes and 13 branches. The characteristics of each branch (length, impedance and connecting buses) can be seen in the following table.

As is usual in a low voltage system, it can be verified that the characteristics of the lines do not usually coincide and are not uniform. At each bus of the system there is an associated load. The characteristics of each load (power and connected phase) are shown in the following table.

As can be seen from the table above, the total power foreach phase of the system is different (R = 40 kW, B = 35 kW, Y =30 kW), causing the system to be unbalanced. Because

Line characteristics				
Sending bus	**Receiving bus**	**Length (m)**	**R (ohm)**	**X (Ohm)**
1	2	62,9	0,01883	0,00461
2	3	12,3	0,00591	0,00093
3	4	49,2	0,02362	0,00373
4	5	36,9	0,01772	0,00279
5	6	24,6	0,01181	0,00186
2	7	19,7	0,00660	0,00145
7	8	29,6	0,00990	0,00218
8	9	49,3	0,01650	0,00364
9	10	45,7	0,01347	0,00335
10	11	45,7	0,01347	0,00335
11	12	45,7	0,01347	0,00335
9	13	87,8	0,04687	0,00667
13	14	58,5	0,03125	0,00445

[a]Line characteristics of the system.

Bus Demands characteristics			
Bus demand	**Power (kW)**	**P.f**	**Phase**
2	10	0,98	R
3	10	0,98	B
4	5	0,98	Y
5	10	0,98	R
6	10	0,98	B
7	10	0,98	Y
8	5	0,98	R
9	5	0,98	B
10	10	0,98	Y
11	10	0,98	R
12	10	0,98	B
13	5	0,98	Y
14	5	0,98	R

[a]Loads characteristics per bus.

of this, each phase of the system has to be studied separately. Regarding which kind of the faults will be tested, the methods will be tested with different types of faults, although some of them as a fault of 3 phases are very rare. The characteristics of the faults are the following:

System fault characteristics			
Fault line	**Fault type**	**Fault resistance (Ω)**	**Fault Location**
2–3	Y-E	10	30% from 2
5–6	R-B-Y	5	75% from 5
7–8	B-Y	50	18% from 7
10–11	R-B-Y	1	92% from 10
13–14	R-E	100	55% from 13

[a]Faults tested with the 2 developed methods.

To calculate the error of the methods with respect to the calculated distance, the following formula is applied. All line lengths are assumed to be 1p.u length. This formula will be applied to calculate the error in the 2 methods.

$$F.\ d.\ error\ (e) = \frac{|Calculated\ distance - Actual\ distance|}{Line\ length} * 100\% \tag{41}$$

For different types of faults and fault resistances, the results obtained after testing the 1º method showed that all the faults are successfully localized and the fault distance is also being estimated with a maximum error of 0.43 %. Based on the testing results from the table above, this fault location algorithm has been verified and the results also shows that the algorithm is not affected by the fault type and fault resistance.

Results of the fault testing					
Fault line	**F. type**	**F.R (Ω)**	**F. Location**	**Estimated Fault Distance**	**Fault Distance Error (e)**
2–3	Y-E	10	30%	30.02% from 2	0.02%
5–6	R-B-Y	5	75%	75.23% from 6	0.23%
7–8	B-Y	50	10%	10.29% from 7	0.29%
10–11	R-B-Y	1	92%	91.57% from 10	0.43%
13–14	R-E	100	55%	54.92% from 13	0.08%

[a]Faults testing results of the 1º developed method.

Results of the fault testing					
Fault line	**F. type**	**F.R (Ω)**	**F. Location**	**Estimated Fault Distance**	**Fault Distance Error (e)**
2–3	Y-E	10	30%	30.09% from 2	0.09%
5–6	R-B-Y	5	75%	75.47% from 6	0.47%
7–8	B-Y	50	10%	10.62% from 7	0.62%
10–11	R-B-Y	1	92%	90.96% from 10	1.04%
13–14	R-E	100	55%	54.79% from 13	0.21%

[a]Faults testing results of the 2º developed method.

For different types of faults and fault resistances, the results obtained after testing the 2º method showed that all the faults are successfully localized and the fault distance is also being estimated with a maximum error of 1.04 %. Based on the testing results from the table above, this fault location algorithm has been verified and the results also shows that the algorithm is not affected by the fault type and fault resistance.

IV. CONCLUSIONS

In this thesis, two PMU-based fault detection and location methods are proposed for the low-voltage network. The 2 methods are based on real-time state estimation. The first method stands out because due to the use of a large amount of μPMU, a total observability of the system is available. Based on this, the SE is based on the topologies of the network that includes a imaginary fault bus. This imaginary fault bus is the one that allows that when comparing the weighted measurement residuals of all the SEs, it is possible to identify the line in which the fault has occurred thanks to the fact that it is the line with the lowest residual. As a negative part of the application of this method is its high cost due to the need to install PMU in all nodes of the system. This makes the application of this method not really economically viable in LV, although in MV it may be more profitable. Despite the cost of this method, it also has many advantages. The total observability of the system means that the topology of the network can be whatever it is and also the presence of DG does not change the performance of the method since the state estimation is not affected by the nature of the loads of generators of the buses.

The second method is also based on SE. Contrary to the first method, there is not a total observability of the system, but by having measurements at the beginning and end of each line it is possible to locate where the fault has occurred by making SE based on those measurements. The fault location is done thanks to an iterative process that consists of SE based on the measurements of the beginning and end of the line, these

SEs will be iterated until they converge in the place where the fault has occurred. This method, unlike the first method, is economically feasible because it uses a much smaller number of μPMUs. It works especially well in radial systems since, although few measurements are available, it is possible to perform the SE without difficulty as long as information on the loads of the system nodes is available.

The validation of both methods has been carried out using a 14 bus low voltage distribution network. The power grid and PMUs are simulated in the time domain using Simulink. Noise was added to the measurements obtained based on the characteristics of the microPMU measurement errors. The data obtained from the simulations are implemented in the algorithms corresponding to each method to check its operation. Faults of all kinds have been simulated in different locations of the system. Both methods have achieved acceptable results since they have been able to locate the faults with a small percentage of error. The first method has better results, that was to be expected since having measurements in all the buses of the system, makes the state estimation more exact.

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