Abstract—This paper presents a method to built a Petri Net (PN) to identify fault location in distribution systems with high penetration of Distributed Generation (DG). The design of PN is based on the composition of single PN, modeling protection systems and current detectors. A case study considering a typical Italian distribution grid is shown. The results highlight that the proposed method can remove a lot of complexity in data analysis also in presence of misoperation of protection systems.

Keywords: Power System Protection, Distributed Power Generation, Distribution systems, Petri Net

I. INTRODUCTION

The interest in identifying the location of faults has considerably increased due to the expected high penetration of Distributed Generation (DG) in distribution systems that introduces some problems such as losing coordination of protection devices resulting in false tripping [1-3]. In fact, when DG is connected to a distribution system, the network will be radial no longer and this means losing the existing coordination among network protection devices [4-6].

It is very important to have automatic methods for the identification of fault location in real time, in order to reduce power supply interruption and enhancing quickly service reliability considering that if the overcurrent is detected rapidly and the circuit breakers that isolate the section with the fault are tripped, the source of ionization can be stopped and normal operation can be restored after short time [7].

Over the last years, much research work has been done in fault diagnosis and identification, so many models, procedures and algorithms have been proposed. Many techniques depend mainly on studying the pattern of the voltage and current waveforms associated with the fault. Among these Fourier analysis based algorithms and FIR filtering based protection. Recently new techniques are presented based on wavelet analysis [8]. In [9-11] expert system (ES) technique have been considered; in particular, in [9] the paper presented a decision support system DSS that automatically creates rules for knowledge representation and develops an efficient fault diagnosis procedure; in [10] a Bayesian network on the basis of expert knowledge and historical data for fault diagnosis on distribution feeder was built and in [11] expertise was represented by logical implications and converted into a Boolean function. Fuzzy approaches have been widely applied to power system fault diagnosis [12-13]. The fuzzy logic technique offers the possibilities to model inexactness and uncertainties of protection device operations and false data. In [12] a method for the fault section estimation that considers the network topology under the influence of a circuit breaker tripped by the previous fault was proposed. To deal with the uncertainties due to the protection systems, the fuzzy set theory was applied to the network matrix in order to examine the relationships between the operated protective devices and the fault section candidates. In [13] a fast diagnosis system for estimating the fault section of power system by using a hybrid cause-effect network and fuzzy logic was presented.

In recent years, Petri Net (PN) and Fuzzy Petri Net (FPN) technique has gained researchers’ strong interest [14-17]. In [14-15], fault clearance process was modeled by PN and a reverse PN to estimate fault section. In [16-17] FPN was used to deal with incomplete and uncertain alarm information of protective relay and circuit breaker.

Up to now, few approaches have considered the identification of the fault location in power system with a high penetration of DG. So, in this paper, in line with what has already been presented in [18], a new method based on PN theory has been developed. It allows to design a careful PN depending on network topology, to observe the behaviours of the protection systems in case of faults and localize fault position in distribution network. The design of PN model is carried out on the composition of single PN models for protection systems and current detectors: such as approach allows to localize the faults also in presence of a strong penetration of DG. In order to validate the proposed method, simulations on a typical Italian distribution systems are carried out. The paper is organized as follows: in the next section will be reminded the basic concepts of PN transition/place, in the section III the PN model of the protection system is presented. In the section IV the method for identification of fault location is shown; a briefly panoramic on Italian protection systems is in section V and simulation and comments are in section VI. At the end, there are the conclusions.

II. PETRI NET BACKGROUND

A Petri Net can be identified as a particular bipartite directed graph characterized by three objects: places (circles),
transitions (bars) and directed arcs connecting places to transitions and transitions to places.

A place can be an input place to a transition if a directed arc connects this place to the transition or an output place of a transition if a directed arc connects the transition to the place. In practice, place and transition model several aspects of a system. Input places may represent the availability of resources, the transition their utilization, output places the release of the resources. An example of a Petri net is shown in Fig. 1. It consists of four places, represented by circles, five transitions, depicted by bars, and directed arcs connecting places to transitions and transitions to places. In this net, for instance, place \( p_1 \) is an input place of transition \( t_1 \) and \( t_2 \). Place \( p_2 \) is output place of transition \( t_2 \) and input of transitions \( t_3 \) and \( t_4 \) and etc. It is noted that from transition \( t_2 \) to place \( p_2 \) there are two arcs.

In order to analyze the dynamic behavior of the modeled system, considering states and their changes, each place may potentially hold either none or a positive number of tokens, pictured by small solid dots, as shown in Fig. 1. The presence or absence of a token in a place can indicate whether a condition associated with this place is true or false or for a place representing the availability of resources, the number of tokens in this place indicates the number of available resources. At any given time instance, the distribution of tokens on places is called Petri Net marking and defines the current state of the system [19].

Let \( Q \) be a Petri Net with a place set \( P \) of \( m \) places \( P = \{ p_1, p_2, \ldots, p_m \} \) and a transition set \( T \) of \( n \) transitions \( T = \{ t_1, t_2, \ldots, t_n \} \). If \( P^+ : P \times T \to \mathbb{N} \) and \( P^- : P \times T \to \mathbb{N} \) are the matrices that specify the arcs from places to transitions and the arcs from transitions to places, respectively, the evolution of PN \( Q \) is given by:

\[
S[k+1] = S[k] + (P^+ - P^-) \cdot \sigma = S[k] + C \cdot \sigma[k]
\]

where \( C = P^+ - P^- \) is the incidence matrix with dimension \( m \times n \), the vector \( S[k] \) is the marking of \( Q \) at the epoch \( k \) with dimension \( 1 \times m \) and \( \sigma[k] \) is the sequence of input transitions of dimension \( 1 \times n \). According to PN theory a transition is enabled at the epoch \( k \) if and only if \( S[k] \geq P^- (c,t) \) where \( P^- (c,t) \) indicates the \( t \)-esima column of \( P^- \). The \( P^- \) and \( P^+ \) matrix for the example in Fig. 1 are the following:

\[
P^- = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad P^+ = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}
\]

where the column correspond to transitions and the rows to the places. The incidence matrix is:

\[
C = \begin{bmatrix} 0 & -1 & 0 & 0 & 1 \\ 0 & 2 & -1 & -1 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}
\]

### III. PETRI NET MODEL FOR A DISTRIBUTION NETWORK FAULT DIAGNOSIS

Protection system (relay with circuit breaker) behaviors are modelled by Petri Nets using information including status of relays, circuit breakers, timestamps and the current direction in correspondence of the relays.

The number of the places depend on the number of the trip thresholds that characterize a single protection system. In Fig. 2 the Protection Petri Net (PPN) model is shown.

The place \( p_p \) represent the initial state of the protection \( p \), and a token in this place means that the protection is ready to detect the current direction and to open the circuit; the transitions \( t_{pm} \) and \( t_{ps} \) indicate that the protection system begins to detect the current direction, the place \( p_{pd} \) or \( p_{pu} \) correspond to the status of "evaluation of the current direction". When a token is in \( p_{pu} \) or \( p_{pm} \) the system is detecting current direction and if the values exceed anomalous set points, transitions \( t_{pRD} \) or \( t_{pRU} \) fire. A token in \( p_{ps} \), \( p_{pp} \) or \( p_{ppd} \) means that main, primary or secondary threshold of the relay \( R \) is now sensing the fault current and the circuit breaker can be activated. Such an action is represented by the firing of transitions \( t_{pm}, t_{pp} \) or \( t_{ppd} \), respectively. So, the final marking with a token in the place \( CB_{pmm}, CB_{pp} \) or \( CB_{ppd} \) means that one of main, primary or secondary CB has operated. The PPN is designed considering the order of CB trips: \( CB_{p}, CB_{p} \) and \( CB_{pp} \). A more general protection system is shown in Fig. 3 where the number of threshold levels is \( n \).

The other important modeled element is the current detector that senses the current direction in correspondence of a particular bus (eg.: DG or load bus). The Detector Petri Net (DPN) model is shown in Fig. 4 and it is a part of the PPN model. The places and transitions have the same meaning as previously described.
allows for higher accuracy in localizing the fault; generator connection points. A high number of detectors in the real protection system; number of relay and CB places equal to the thresholds levels of steps to design the PN are the following:

- Insert a DPN model in correspondence of a load or current detectors. Their marking will indicate the location fault. Such an evaluation will be done by evolving the PN evolution of the PN will be able to provide information on the location of the fault when the i-transition corresponding to i-FLT, for any power branch between two protection systems and/or current detectors. Their marking will indicate the location of the fault;
- Evaluate current faults and record all current direction in all branches considered at the step 4;
- Connect PPN and DPN to the inserted FLP: if in correspondence of a fault in a section modeled by i-FLP the current in the protection system flows downstream (upstream), connect place $p_{ud}$ ($p_{du}$) to i-FLP.

It is noted that if downstream of the protection system there aren’t generators, the connection specified at point 5, must not be carried out.

### B. Localization of the Faults

The second step is based exclusively on the evolution of the PN model according to the design rules: the natural evolution of the PN will be able to provide information on the location of the fault when the i-transition corresponding to i-FLP will be fired. An example could illustrate the procedure. Let consider a simple section of distribution network (Fig. 5) with a fault between bus B2 and B3. Assuming that in correspondence of P1 and P2 current direction is downstream while in P3 it is upstream, due to current contribution of generator in B7, in order to detect that the fault is on the line 1 (L1), the PN scheme will be formed by three PPN models as shown in Fig. 6.

![Figure 4. A general DPN model of current detector](image)

![Figure 5. A section of power network](image)

In this case, the protection system is characterized by three circuit breakers leaded from their relays. Protection P1 has two trip thresholds and protections P2 and P3 have three thresholds. The connection between $p_{ud}$ ($p_{du}$) and the PPN $p_{L1}$ and $p_{L2}$ is carried out according to the design procedure. If at the end of the PN evolution a token is at the added FLP $p_{ud}$, the fault is on the line 1. If a more accurate location of the fault must be obtained, also detectors have to be integrated in the scheme. In particular, detectors can be connected in correspondence of buses and modeled according to the scheme in Fig. 4. In the previous example, if a detector is in correspondence of the generator in B4, the DPN model is inserted into PN as shown in the circle in Fig. 6: when the final token is in $p_{L1}$, it can deduce that the fault is localized before bus B4.
opened the switches of emergency ties, that can provide alternative paths to power flows in case of outages or programmed interruptions.

Commonly, radial structure is formed by main feeders supplied by a Primary Substation (PS) and lateral ties. Feeders are connected to MV/LV substations and often to satellite centres (CSs), that are switching buses used to connect feeders among them, create additional possibilities for connection and increase reliability by means of other protection devices.

At present overcurrent protection relays are set according to DK 4452 standard [20].

The MV side of the PS is protected by a maximum current time independent relay with a single threshold for intervention. This protection is designed to protect the PS by possible overload and like reserve to protective MV feeder. Protection against single fault is ensured by a maximum omopolar voltage protection acting on the side HV and MV. MV feeders are protected against single earth-faults by directional varmetric relay or wattmetric with three trip thresholds, multi-phase faults by overcurrent relay with three trip thresholds.

Furthermore, in presence of SCs the relay in PS for feeder protection is replaced for the out going lines from SC but with two coordinated trip thresholds. The coordination planning depending on the size of the transformer in PS. In the PS, often for overhead lines, an automatic reclosing device is also installed. It is used in case of temporary faults in order to limit long outages.

The connection of DG in distribution system can cause several problems to operation of the protection system because it involves increasing fault current and a redistribution of short circuit currents in the network. For this reason protections defined and set to passive operation may be subject to delays of intervention that temporarily extend the solicitation of the network in the presence of short circuit. Furthermore, if DG shares in the fault current from adjacent feeder, selectivity between the protections of the line could be lost and the interruption of the power supply involves also users not connected to a fault feeder [2,21].

VI. SIMULATION AND RESULTS

In order to illustrate the introduced method, a typical Italian distribution network is used. The single line diagram of the distribution system is presented in Fig. 7.

The considered radial network is characterized by two satellite centres and several branches starting from three main feeders. This gives great coordination complexity to the protection system that must be able to handle two-way power flow in distribution system with DG. Furthermore, it is assumed that there is a control center that monitors the behavior of the protection system.

By means of PowerWorld 9.0 program, in any branch all short circuit currents are calculated and for our purpose, the three phase fault is considered at section CS2-CS1, on the link between the two CS. The protective relays R12, R11, R7, with their circuit breakers CB12, CB11 and CB7, respond to the fault and the information is communicated to the control centre.
So, the fault location can be detected by analyzing the evolution of PN model shown in Fig. 8, where only the connection to the FLTs and detection PN parts are considered. By analyzing PN evolution, the protection systems that sense the fault are 15, 11, 10, 12 and 7. The fault current direction detected are indicated in table 1. It is noted that the current direction is evaluated respect to the orientation of distribution network in the Fig. 7.

So, the final state of PN presents a token in the FLP pR10_cs1, so that even though relays and CB have operated correctly, there were incorrect trips: all loads connected to feeder E has been unsupplied. A correct coordination among relays could have minimized the disservice because the R10, R7 relays with their CBs would be tripped.

This example shows how the possibility to have a tool able to inform in real time about the status of the protection system allows to correct anomalies in the operation and offer greater reliability to the power system.

<table>
<thead>
<tr>
<th>PROTECTION SYSTEM</th>
<th>CURRENT DIRECTION</th>
</tr>
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<tbody>
<tr>
<td>15</td>
<td>Right</td>
</tr>
<tr>
<td>11</td>
<td>Right</td>
</tr>
<tr>
<td>10</td>
<td>Downstream</td>
</tr>
<tr>
<td>12</td>
<td>Left</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
</tr>
</tbody>
</table>

Figure 7. A typical distribution Italian system

Figure 8. PN model for distribution Italian system
VI. CONCLUSION

In this work a new PN model for fault identification and location in distribution power system is developed. It is based on the design of PN for the power network topology under test. The design of PN model has been carried out considering two PN model: protection system and current detector.

The presented method allows to deal with distribution systems with high penetration of DG that introduces problems such as losing coordination of protection devices with consequence false tripping.

The method has been validated by means of simulation on a typical Italian distribution network, characterized from different protection devices that require complex coordination.

The effectiveness of the method has been demonstrated by means of a critical case study related to protection systems and DG. In the case study, in presence of a three phase fault, the loss of coordination in protection system is detected and the correct location of fault is obtained. By results it’s clear that the proposed method can remove a lot of complexity in data analysis and allow managing few information while avoiding cascading failure in power protection system. The proposed method has a great potential for use in real time applications and is able to provide historical data for electric utilities in order to better provide reliable energy service.

REFERENCES


