Failure Identification in Smart Grids Based on Petri Net Modeling

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***Abstract*—This paper presents a method to identify and localize failures in smart grids. The method is based on a carefully designed Petri net (PN) that captures the modeling details of the protection system of the distribution network and allows the detection/identification of failures in data transmission and faults in the distribution network by means of simple matrix operations. The design of the PN model is carried out by carefully composing multiple PN models for single protection systems: Such an approach allows the identification of the faults despite possible strong penetration of distributed generation. In order to verify the method, two case studies are discussed. The results highlight that the proposed method can remove a lot of the complexity of the associated data analysis despite the possible presence of malfunctioning protection systems and misinformation due to communication and other errors.**

***Index Terms*—Communication systems, information technology, Petri nets (PNs), power distribution protection, smart grid.**

I. Introduction

The rapid developments of information and communication technology (ICT), and power monitoring and metering technologies are having a significant impact on power systems. In fact, the integration of new technologies allows utilities and suppliers to rethink network design and operation in order to improve efficiency, quality, and reliability. These emerging capabilities open the doors to a new concept for power networks: the smart grid [1], [2]. Smart grids are based on the installation of infrastructures and the implementation of data integration with automated analysis of the event data provided at various substations. The infrastructure includes communication and monitoring equipment with most of the monitoring functions provided at the substation via intelligent electronic devices [3].

This vision of power systems allows the implementation of new network management strategies in order to reduce costs by applying demand side management, enabling grid connection of distributed generation (DG), incorporating grid energy storage for DG load balancing, and identifying, eliminating, or containing failures, such as widespread power grid cascading failures. The latter problem is particularly acute in emerging power systems and makes quick fault diagnosis and identification essential for pinpointing the faulted elements and their position in the power grid. Furthermore, the fault diagnosis and identification problem under the "smart grid philosophy" must address both the possibility of communication failures and the correctness and consistency of the information conveyed to control centers by ICT systems, whose development is strongly encouraged by policy and regulatory initiatives [1], [4]. For example, in 2009, the U.S. government announced the largest single energy grid modernization investment in history, funding a broad range of technologies that will spur the nation's transition to a smarter, stronger, more efficient, and reliable electric system [5].

In recent years, much research work has been devoted to fault diagnosis and identification, and a variety of models, procedures, and algorithms have been proposed. In [6]–[8], expert system techniques have been considered; in particular, [6] presents a decision support system that automatically creates rules for knowledge representation and develops an efficient fault diagnosis procedure. In [7], a Bayesian network for fault diagnosis on the distribution feeder was built on the basis of expert knowledge and historical data, and in [8], expertise was represented by logical implications and converted into a Boolean function. Different methods for more general systems have been pointed out: In [9], an intelligent supervisory coordinator for process supervision and fault diagnosis in dynamic physical systems was presented, a mode identification method for hybrid system diagnosis was introduced in [10], and, in [11], the authors proposed a scheme of applying wireless sensor networks for online and remote energy monitoring, and for fault diagnostics for industrial motor systems.

Fuzzy logic approaches have been applied to power system fault diagnosis in [12]–[14]. These techniques offer the possibility to model inexactness and uncertainties created by protection device operations and incorrect data. Min [12] propose a method for fault section estimation that considers the network topology under the influence of a circuit breaker tripped by a preceding fault. To deal with the uncertainties due to the protection systems, fuzzy set theory was applied to the network matrix in order to examine the relationship between the operated protective devices and the fault section candidates. In [13], a fast diagnosis system for estimating the faulty section of a power system by using a hybrid cause–effect network and fuzzy logic was presented. Applications for fault

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detection and diagnosis in motor drives were also presented in [14].

In recent years, Petri net (PN) and fuzzy PN (FPN) techniques have received significant attention by researchers [15]–[19]. In [15] and [16], the fault clearance process was modeled by a PN, and a reverse PN was introduced to estimate the fault section. In [17] and [18], an FPN technique was used to deal with incomplete and uncertain alarms generated by protective relays and circuit breakers. In [19], PNs were applied to a supervisory control scheme for human–machine interface systems.

Up to now, the fault diagnosis methods have not considered the significant influence of ICT in power systems, and few approaches have been developed to integrate methods to detect both faults in distribution networks and failures in communication systems. Furthermore, the presence of DG is typically not taken into account when anomalous situations arise.

In this paper, we develop a method based on PN theory for performing failure diagnosis in smart grids, where the term failure is reserved for both power and communication system failures. The proposed method exploits the underlying network topology in order to carefully design a PN, both to detect failures in data transmission and to identify faults in the distribution network. The use of a PN model allows the description of events that occur simultaneously. Since, in power networks, a fault can activate simultaneous events (trip of the protection, data transmissions, etc.), a PN proves to be a very suitable modeling tool for this purpose. The design of the PN model is carried out by systematically composing multiple PN models for single protection systems and current detectors: Such an approach allows also the identification of the faults in the distribution system despite possible strong penetration of DG. This makes the proposed approach substantially different from those adopted in [20] and [21], where only the failure detection algorithm has been considered without giving the opportunity to identify the fault location. In order to validate the proposed method, simulations on typical distribution systems are carried out.

II. PN Background

In order to describe a chain of events (e.g., the tripping of a protection system), it is often necessary to represent activities that occur in parallel with each other but not independently: For example, a given event may not be allowed to occur or activate unless other activities conclude or certain conditions hold. In power systems, PNs have already been used to evaluate reliability and security, and to simulate the behavior of the protection systems [22], [23].

A PN is a mathematical model that allows not only the representation and description of an overall process but also the modeling of the process evolution in terms of its new state after the occurrence of each event. PNs can be represented by a graph that can be used as a visual communication aid with the ability to simulate the dynamic and concurrent activities of the underlying system. As a mathematical tool, a PN allows the specification of state evolution equations, together with algebraic relations governing the behavior of the system [24].

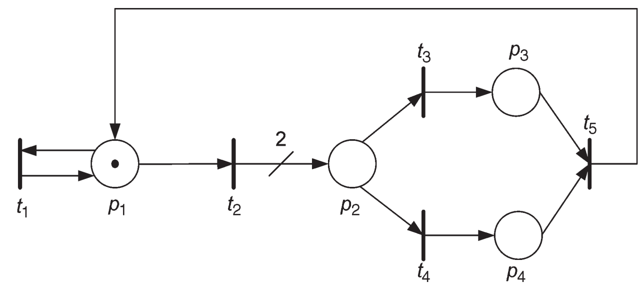

Fig. 1. PN example.

Graphically, PNs can be identified as a directed bipartite graph with two sets of nodes, (circles) places and (bars) transitions, and (arrows) directed arcs connecting places to transitions or transitions to places. An example of a PN 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. Places, transitions, and arcs model the process state, the events that occur, and the evolution laws of the process, respectively. The actual process state is identified by the position of tokens in the places. The number of tokens at places changes when some event happens (transition firing). Typically, input places represent the availability of resources, transitions represent their utilization, and output places represent the release of resources.

In the net of Fig. 1, for instance, place p_1 is both an input and an output place of transition t_1 and an input place of transition t_2. Place p_2 is the output place of transition t_2, the input place of transitions t_3 and t_4, and so forth. Note that, from transition t_2 to place p_2, there are two arcs, which is sometimes denoted by a single arc of weight 2. When transition t_2 fires, it removes one token from place p_1 and deposits two tokens to place p_2; the tokens at place p_2 then become available to transitions t_3 and t_4.

In order to analyze the dynamic behavior of the modeled system by considering its state evolution (token changes at places), we need to keep in mind that each place may hold a nonnegative number of tokens, pictured by small solid dots, as shown in Fig. 1. The presence or absence of a token in a place indicates whether a condition associated with this process state 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 in places is called the *PN marking* and defines the current state of the system [24], [25].

Formally, we let $Q = (P, T, P^-, P^+)$ be a PN with a place set P of n places $P = \{p_1, p_2, \ldots, p_n\}$, a transition set T of m transitions $T = \{t_1, t_2, \ldots, t_m\}$, and $P^- : P \times T \rightarrow N$ and $P^+ : P \times T \rightarrow N$ representing the matrices that specify the arc weights from places to transitions and the arc weights from transitions to places, respectively (N is the set of nonnegative numbers with a zero representing the absence of an arc) [24]. Specifically, $P^-(i,j)$ is the weight of the arc from place p_i to transition t_j, and $P^+(i,j)$ is the weight of the arc from transition t_j to place p_i. The evolution of PN Q is given by

$$\underline{S}[k+1] = \underline{S}[k] + (\underline{P}^+ - \underline{P}^-) \cdot \sigma[k] = \underline{S}[k] + \underline{M} \cdot \sigma[k] \quad (1)$$

where $\underline{M} \equiv \underline{P}^{+} - \underline{P}^{-}$ is the incidence matrix and has a dimension of $n \times m$, the vector $S[k]$ is the marking of Q at time epoch k of dimension $n \times 1$, and $\sigma[k]$ is the firing vector of dimension $m \times 1$, which serves as an indicator vector, indicating the transition that fires at time epoch k.

According to PN theory, transition $t_j \in T$ is enabled at time epoch k if and only if each input place p_i to transition t_j has a number of tokens greater than or equal to the weight of the arc between p_i and t_j; this statement translates to $\underline{S}[k] \geq \underline{P}^{-}(:, t_j)$, where $\underline{P}^{-}(:, t_j)$ indicates the t_j column of $\underline{P}^{-}$ [14]. The $\underline{P}^{+}$ and $\underline{P}^{-}$ matrices for the example in Fig. 1 are the following:

$$\underline{P}^{-} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \underline{P}^{+} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

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

$$\underline{M} \equiv \underline{P}^{+} - \underline{P}^{-} = \begin{pmatrix} 0 & -1 & 0 & 0 & 1 \\ 0 & 2 & -1 & -1 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{pmatrix}.$$

At the time epoch $k = 0$

$$\underline{S}[0] = [1\ 0\ 0\ 0]^{\mathrm{T}}$$

and the firing of transition t_2 causes

$$\underline{S}[1] = \underline{S}[0] + \underline{M} \cdot [0\ 1\ 0\ 0]^{\mathrm{T}} = [0\ 2\ 0\ 0]^{\mathrm{T}}.$$

Depending on the underlying modeling assumptions, the firing of transition t_2 may indicate the occurrence of an event (e.g., trip of a circuit breaker) that causes the system to transition to another state (e.g., opened circuit breaker). In our examples later on, we will use the PN to capture and interpret activity that occurs in the system. Due to faults that may occur in the system, the number of tokens in places can become negative. This is not a violation of any physical constraints but rather a result of the interpretive nature of our PN models.

III. PN Model of Distribution Network for Fault Diagnosis

In this paper, we do not explicitly take into account timing information (because we employ untimed PNs), but the order of activation of different relays (main, primary, secondary, etc.) is captured by the PN model. One can potentially extend these ideas in a context that includes timing information by employing timed PNs [26].

The behavior of protection systems (relays with circuit breakers) can be modeled by PNs in which relays and circuit breakers are modeled by places of the PN. The number of places of the proposed PN model depends on the number of trip thresholds that characterize a given protection system. Fig. 2 shows the *protection PN* (PPN) model for a three-threshold protection system, which can be generalized to a different number of trip thresholds in a straightforward manner. In the remainder of this section, we describe the PN model of a protection system in detail.

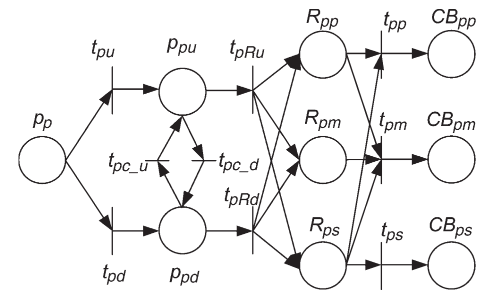

Fig. 2. PN model of protective relay.

The PN model is built assuming the following operational hypotheses for each protection system: 1) Each protection system is capable of detecting the current direction; 2) it is possible to obtain from relays information regarding the status of "ready to send the main, primary, or secondary trip signal to the circuit breaker"; 3) it is possible to obtain information regarding the tripped threshold at which the circuit breaker opened; and 4) all events described before are observable, can be sensed, and can be conveyed by a communication system.

Given the advent of ICT, the aforementioned hypotheses become increasingly realistic. For example, sensors and communication devices that are available at relays and circuit breakers may be tasked with providing the information required in items 2) and 3).

In terms of the PN model, the available information from the sensors (as current directions, trips, etc.) is associated to events described by transitions, and the status of the protection system is described by places. In particular, place p_p represents the initial state of the protection, when its state is that of monitoring the current direction. Places p_{pd} and p_{pu} correspond to the status of "evaluation of current direction": In particular, if a token is in p_{pu}, the current through the protection is upstream, whereas if the token is in p_{pd}, the current is downstream. Transitions t_{pu} and t_{pd} indicate that the protection system has begun to detect the corresponding current direction. While in state p_{pu}, a change of current direction causes transition t_{pc_d} to fire; similarly, while in state p_{pd}, a change of current direction causes transition t_{pc_u} to fire. When a token is in p_{pu} or p_{pd}, the system has detected current direction, and if the values exceed certain anomalous set points, transition t_{pRd} or t_{pRu} may fire. A token in R_{pm}, R_{pp}, or R_{ps} means that the main, primary, or secondary threshold of the relay R_p 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}, and t_{pr}, respectively. Thus, the final marking with a token in place CB_{pm}, CB_{pp}, or CB_{ps} means that the main, primary, or secondary CB has operated. The PPN is designed assuming the following temporal order of CB trips: CB_m, CB_p, and CB_s. This is reflected in the PN model by ensuring that if CB_{pm} trips, no tokens remain in R_{pp}, R_{pm}, and R_{ps}, whereas if CB_{pp} trips, no token remains in R_{pp} and R_{ps}. As mentioned earlier, more general PPN models for protection systems with a different number of threshold levels can be devised in a similar manner.

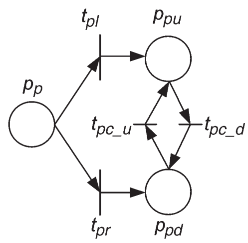

Fig. 3. General DPN model of current detector.

An important part of the proposed PPN model is the *current detector* which senses the current direction in correspondence to a particular bus (e.g., DG or load bus). It can be associated with a directional relay that sends the information of the current direction by using a communication system [27], [28]. The *detector PN* (DPN) model is shown in Fig. 3. The places and transitions have the same meaning as described earlier when commenting on Fig. 2. In the following, the current detector and its PN model will also be used without associating it to a circuit breaker in order to detect only the current direction in the grid.

IV. Methodology for Failure Detection

When one or more failures occur, protection systems and detector currents reach certain values and/or indicate certain activity. We assume that such information is available to a *reasoner*, who needs to assess its coherence. The reasoner can be a SCADA system that, by means of a remote terminal unit (RTU) and communication channels, receives and assesses data. The proposed method for failure detection and identification is based on a new strategy that consists of carefully designing a PN model that captures all protection systems and current detectors, as well as their activity. Employing the proposed PN model, the reasoner is able to diagnose the fault position, also determining in the process whether incorrect data were provided to the reasoner.

More specifically, the proposed fault diagnosis method is based on the following three steps: 1) development of a PN model appropriate for failure detection; 2) detection of data transmission failures; and 3) identification of power system faults.

The first step allows the design of a PN suited for the analysis of the given power system, the second step identifies failures in data transmission and/or false trips, and the third step, which occurs only if the second one is successful, identifies the actual fault position.

A. Design of PN for Failure Detection

The design of the PN depends on the characteristics of the underlying power network in terms of both connected DG and protection systems. In particular, the expected degree of accuracy depends on the sensing information available at the corresponding DG and protection systems. The number of generators affects the possibilities for fault current direction, and the protection systems determine the complexity of the PN in terms of places and transitions.

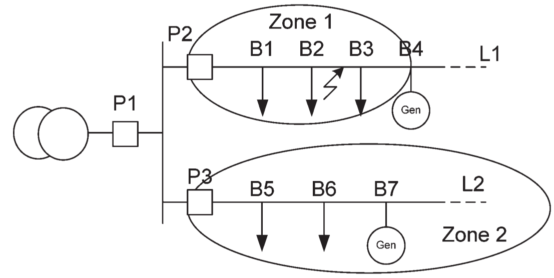

Fig. 4. Section of power network.

The design procedure is now illustrated via an example. Specifically, we consider the section of the distribution network shown in Fig. 4, assuming a smart grid with adequate sensor availability (as described in Section III).

In the first step, each protection system is considered, and its associated PPN model is constructed (refer to Fig. 2). In this example, the network consists of three protection systems ($P1$, $P2$, and $P3$), so we construct three PPN models. The structure of each PN depends on the number of threshold levels of each single protection system. Assuming that $P1$ consists of two threshold levels, and both $P2$ and $P3$ consist of three threshold levels, we construct the three PPNs according to the rules presented in Section III; the resulting scheme is shown in Fig. 5. The second step inserts the DPN models corresponding to the buses that have sensors for recognizing the current direction. Assuming the existence of a sensor at bus $B4$, to account for the presence of the generator, one DPN is added to the PN, as shown in the circled part of Fig. 5.

The PN shown in Fig. 5 has unequal (not unity) weights, unlike the PPNs introduced in Section III. The reason is the need to be able to localize faults and it will become clearer later. As we will see, if the PN is constructed according to a simple composition of the single PPNs, it will not be capable of localizing the faults. It will also be necessary to add a number of places that correlate the information obtained from the constructed PNs.

In this example, we are interested in localizing the faults on line 1 ($L1$), between protection $P2$ and the generator at bus $B4$, and on line 2 ($L2$), downstream protection $P3$. The part of the network between protection $P2$ and bus $B4$ will be named *zone 1*, and the part between $P3$ and the end of the line $L2$ will be named *zone 2*. Thus, we need to add places that we call place location faults (PLFs). The first PLF is p_{L1} and accounts for zone 1, and the second is p_{L2} and accounts for zone 2. In order to correlate the information, the connections between the constructed PNs and the two PLFs must be taken into account. Note that a fault between bus $B4$ and protection $P2$ is supplied from both the generator and the substation, resulting in a downstream current in protections $P1$ and $P2$, and an upstream current in $B4$ and $P3$. This observation suggests that we should connect places p_{1d}, p_{2d}, p_{3u}, and p_{gen} to place p_{L1}. The same reasoning can be applied to place p_{L2} (fault in zone 2), keeping in mind that the only PN on line 2 is associated to protection $P3$. Obviously, the connections are carried out by means of the two transitions t_{L1} and t_{L2}, which model the sensors at a control center that is able to gather and indicate

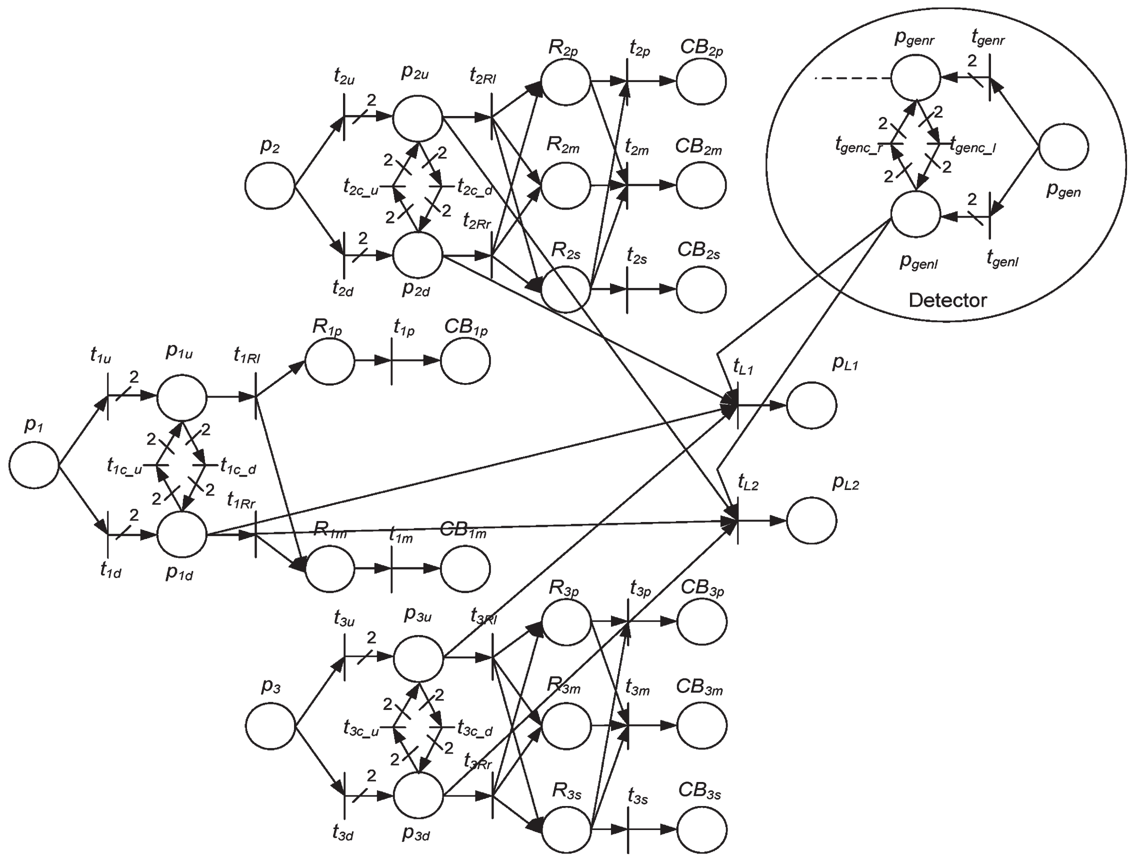

Fig. 5. PN model for the power system section in Fig. 4.

the fault location. Clearly, the PN can evolve correctly only if we consider two tokens in correspondence of the input and output arcs of the places p_{pu} and p_{pd}, as shown in Fig. 5. In the example, with two tokens in p_{2d} (the protection system is detecting the current direction), we can have both the following: 1) Relay 2 senses an anomalous value of the current and transition t_{2Rr} fires (so that the first token is placed in R_{2p}, R_{2m}, and R_{2s}), and 2) (when all sensors detect the current direction with tokens in p_{2d}, p_{1d}, p_{3u}, and p_{genl}, and the control center receives such information) transition t_{L2} fires and the second token placed in p_{L1}. The marking of p_{L1} indicates that the fault is on feeder $L1$, in zone 1.

Summarizing, the steps that are followed to systematically design the PN model for each protection system are the following: 1) Insert a PPN model for any protection system with a number of relays and CB places equal to the number of threshold levels of the corresponding protection systems. 2) Insert a DPN model in correspondence of a load or generator connection points. A higher number of detectors allow for greater accuracy in the identification of faults. 3) Insert a PLF for any power branch between two protection systems and/or current detectors. Their marking will indicate the position of the fault. 4) Connect the PPN and DPN to the inserted PLF: Connect place p_{pd} (p_{pu}) to i-PLF if, in correspondence to a fault in a section modeled by i-PLF, the current in the protection system flows downstream (upstream).

It is noted that if the downstream protection system does not posses any generator, the connection specified at step 4) is not carried out.

B. Procedure for Data Transmission Failure

This procedure uses the PN model and the data, to reconstruct its evolved state and identify the failures via parity checking operations, usually based on integer arithmetic or taken modulo p (according to the finite Galois field $GF(p)$, where p is a prime number). The method has already been used in [20] and [21] and is detailed in [29] and [30]. Here, only the features required for reproducing the results obtained in subsequent sections are reported.

The existing approach encodes the state of the original PN by embedding it into a *redundant* one in order to enable the diagnosis of failures in PN transitions and/or places. For this purpose, it assumes that the PN activity (transition firing) is observable and the PN state is periodically observable. A related work on fault-tolerant controller implementation using error-correcting codes over Galois fields has been proposed in [31].

In order to detect data transmission failures or/and false trips in the protection system, the concepts of transition and place faults must be recalled. A *transition fault* occurs at transition t_j if either of the following happens: 1) Transition t_j fires and no tokens are deposited to its output places, even though all tokens from the input places are consumed (*postcondition failure*), or

2) no tokens are removed from the input places of transition t_j, but all tokens are correctly deposited to its output places (*precondition failure*). A *place fault* occurs at place p_i if the number of tokens in the place is corrupted.

In order to identify faults in a PN, a redundant PN Q_H is constructed. We design the redundant PN Q_H via modulo p operations according to a linear error-correcting code over the finite field $GF(p)$. In particular, assuming the PN introduced in (1), d places are added to the original PN Q such that

$$\underline{S}_H[k] = \begin{bmatrix} \underline{I}_n \\ \underline{C}^* \end{bmatrix} \underline{S}[k] \tag{2}$$

for all epochs k. In (2), $\underline{I}_n$ is an $n \times n$ identity matrix and C^* is a $d \times n$ nonnegative integer (modulo p) matrix to be designed.

The evolution (1) of the redundant PN can be parameterized as

$$\begin{aligned}\underline{S}_H[k+1] &= \underline{S}_H[k] + \begin{bmatrix} \underline{P}^+ \\ \underline{C}^* \underline{P}^+ - \underline{D} \end{bmatrix} \underline{\sigma}[k] - \begin{bmatrix} \underline{P}^- \\ \underline{C}^* \underline{P}^- - \underline{D} \end{bmatrix} \underline{\sigma}[k] \\ &= \underline{S}_H[k] + \underline{\Gamma}^+ \underline{\sigma}[k] - \underline{\Gamma}^- \underline{\sigma}[k] \end{aligned} \tag{3}$$

where D is a $d \times n$ nonnegative integer (modulo p) matrix, also to be designed. The d additional places, together with the n original places, form the places of the *redundant PN embedding* Q_H. Note that, due to the interpretive nature of the redundant PN (and due to the presence of failures), the number of tokens in its places can become negative.

In order to identify transition and/or place faults, let $\underline{e}_T^+$, $\underline{e}_T^-$, and $\underline{e}_P$ denote the indicator vectors of postcondition, precondition, and place faults, respectively, within the epoch interval $[1, 2, \ldots, K]$. Incorporating precondition or postcondition faults and place faults, the erroneous PN state at epoch K is given by

$$\underline{S}_f[K] = \underline{S}[K] - \underline{\Gamma}^+ \cdot \underline{e}_T^+ + \underline{\Gamma}^- \cdot \underline{e}_T^- + \underline{e}_P. \tag{4}$$

In order to detect failures, a *syndrome vector* is introduced and assessed. At epoch K, the syndrome vector is defined as $\underline{s}[K] = F\underline{S}_f[K]$ for $F \equiv [\underline{C}^* \ \ -\underline{I}_d]$ and can be shown to satisfy

$$\underline{s}[K] = \underline{D}\left(e_T^+ - e_T^-\right) + [-\underline{C}^* \ \underline{I}_d]\underline{e}_P \tag{5}$$

and be identically zero if no faults have taken place ($\underline{e}_T^+ = 0, \underline{e}_T^- = 0, \underline{e}_P = 0$).

Place faults at epoch K are detected first by evaluating the place failure syndrome modulo p, in which case (due to the particular construction in [29] and [30]) the failure syndrome is verified to be

$$\underline{s}_P[K] = [-\underline{C}^* \quad \underline{I}_d]\underline{e}_P (\bmod p). \tag{6}$$

Supposing no place faults ($\underline{e}_P = 0$) or assuming that all place faults are correctly identified, the transition failure syndrome at epoch K is verified to be

$$\underline{s}_T[K] = \underline{D}\left(e_T^+ - e_T^-\right). \tag{7}$$

Clearly, the syndrome $\underline{s}_T[K]$ cannot be used to identify multiple faults in which a precondition and a postcondition failure affect the same transition.

Thus, the structure of matrices D and C (which are design parameters) determines the number of faults that can be detected/identified.

Such a procedure can be applied to any power system model previously introduced in order to monitor the PN evolution (as long as the status—number of tokens at each place—becomes periodically available). As mentioned earlier, the number of (place and transition) faults that can be detected/identified depends on the rank properties of matrix $[\underline{D} \quad -\underline{C}^* \ \ \underline{I}_d]$ [21], [29].

C. Identification of Faults

The identification of faults is based exclusively on the evolution of the built PN model according to the design rules, as indicated in Section IV-A. The natural evolution of the PN provides information on the position of the fault when transition t_i, corresponding to i-PLF, becomes enabled.

We illustrate the fault identification procedure by using the network in Fig. 4. In this case, omitting the PN of the detector at the DG bus (PN in the circle), the protection system is characterized by three circuit breakers with their relays. As mentioned earlier, protection $P1$ is assumed to have two trip thresholds, and protections $P2$ and $P3$ are assumed to have three trip thresholds. The connection between p_{pd} (p_{pu}) and PLF places p_{L1} and p_{L2} is carried out according to the design procedure. If, at the end of the PN evolution, transition t_{L1} can fire (so that we end up with a token in p_{L1}), the fault is on line 1; otherwise, if t_{L2} can fire (so that we end up with a token in p_{L2}), the fault is on line 2.

If a more accurate identification is required, detectors have to be integrated in the scheme. In particular, detectors can be connected in correspondence to buses and can be modeled according to the scheme in Fig. 3. In the previous example, if a detector is in correspondence to the generator in $B4$, the DPN model is inserted into the PN model, as shown in the circle in Fig. 5: When the final token is in p_{L1}, the reasoner can deduce that the fault originated before bus $B4$. It is noted that, without the detector, the system was able to localize the fault, specifying only the faulted line ($L1$); with the detector, the system is able to localize the fault on line 2, between protection $P2$ and bus $B4$.

V. Case Studies

In order to evaluate the proposed methodology, a typical radial distribution network is used, as shown in Fig. 6 [32]. Even though the method is independent from the type of fault in the network, all short-circuit currents in branches of this example have been calculated by means of the PowerWorld 9.0 software (in order to know the power flow directions and the current values in correspondence of the protection systems, thus presenting a more realistic case study). The considered radial network is characterized by two satellite centers (two substations characterized by one input, an MV feeder, and

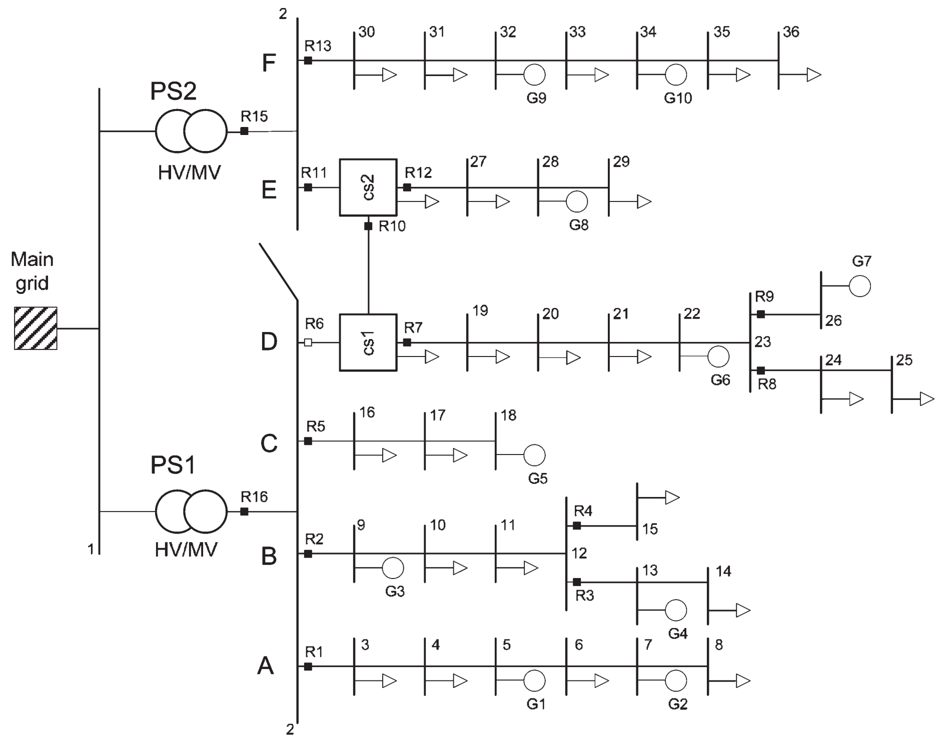

Fig. 6. Typical radial distribution system.

several protected MV output lines) and six feeders starting from two HV/MV substations. The position of the relay/circuit breaker, which is typical in many countries (e.g., Italy [33]), requires significant coordination for the protection system to be able to handle two-way power flow in a distribution system with DG. It is assumed that there is a control center (reasoner) that monitors the behavior of the protection system.

Two scenarios are considered: 1) Scenario 1: Incorrect data are transmitted to the control center (SCADA—reasoner) from protection devices (RTUs) and 2) scenario 2: correct data are transmitted to the control center (SCADA—reasoner) but incorrect relay trips are carried out. The two case studies concern a failure in the communication system (reasoner receives partially incorrect information from the protection system—scenario 1) and a failure in the protection trip mechanism (scenario 2). These problems are solved separately only to clarify the discussion. However, they may occur simultaneously and still the scheme would adequately resolve them (as long as enough sensing capability is available). It is noted that, even though the same network for both case studies has been used, the method is quite general and can be applied to any other test case. The considered network is complex in terms of protection system, so that both scenarios can be presented.

A. Scenario 1

A three-phase fault occurs at section $bus2{-}cs2$ of feeder E, and protective relays $R12$, $R11$, and $R10$, with corresponding circuit breaker numbers $CB12$, $CB11$, and $CB10$, respond to the fault. These operations are correct because they do not allow the fault to be supplied by both $PS2$ and $G6$, and $G7$ and $G8$. However, suppose that the following information arrives at the control center: Relays R_{11m} and R_{11p} have sent the trip signal to $CB11$; CB_{11m} is reported open and CB_{11p} is unknown; in regard to protection 10, current downstream is detected, relay R_{10m} has sent the trip signal to CB_{10m}, and the status of CB_{10m} is reported open; and, regarding protection 12, current upstream is detected, relay R_{12m} has sent the trip signal to CB_{12m}, and the status of CB_{12m} is reported open.

In order to analyze the validity of the aforementioned information, the control center can run the proposed procedure, presented in Section IV-B, having designed the PN according to Section IV-A. In particular, in this case, three protection systems send data to the control center while protection devices 13 and 15, installed in $PS2$ and at the beginning of feeder F, are crossed by the fault current but do not send any signal.

As far as scenario 1 is concerned, the evaluation of the correctness of the received messages (Section IV-B) is assessed for each protection system that sends a message to the control center. In this case study, the procedure for identifying incorrectly transmitted data is applied only to PPN model 11, which is considered suspicious because it sends two signals to the control center (trip signals from R_{11m} and R_{11p}). The corresponding PPN model, consisting of three threshold levels, is the one already shown in Fig. 2 under the condition that the protection subscript number is 11. Here, the PN part related to location fault localization does not come into play because scenario 1 faces only an incorrect data detection problem (this part will be important for scenario 2). For this reason and without loss of generality, all weights are set to unity for simplicity. Furthermore, it is noted that p_{pr11} and p_{pl11} imply a current toward the right side and the left side of Fig. 6, respectively.

We now briefly illustrate the procedure of designing a redundant PN Q_H for the PPN in Fig. 2, with $n = 9$ places and $m = 9$ transitions. The initial marking of the PPN is

$$\underline{S}[0] = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^{\mathrm{T}}.$$

The calculations are carried out modulo p, with $p = 13$. As mentioned earlier, in order to use modulo p operations, it is necessary to assume that all transitions are physically observable, e.g., there exist sensors that indicate whether transitions $t_{11l}, t_{11r}, t_{11c\_l}, t_{11c\_r}, t_{11Rl}, t_{11Rr}, t_{11p}, t_{11m},$ and t_{11s} have fired. Now, two places are added to the original PPN Q, and matrices C^* and D are chosen to be

$$\underline{C}^* = \begin{pmatrix} 9 & 3 & 11 & 3 & 8 & 11 & 2 & 2 & 9 \\ 11 & 10 & 11 & 12 & 10 & 3 & 3 & 7 & 5 \end{pmatrix}$$

$$\underline{D} = -13 \times \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & 4 & 9 & 3 & 12 & 10 & 10 & 12 & 3 \end{pmatrix}.$$

The $\underline{D}$ and $\underline{C}^*$ matrices are designed so that the syndrome vectors in (6) and (7) are unique for any single place fault or single transition fault [20], [21]. With these choices, matrices Γ^- and Γ^+ in (3) become

$$\underline{\Gamma}^- = \begin{array}{cc} \left[\begin{matrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 22 & 35 & 50 & 55 & 68 & 89 & 105 & 126 & 128 \\ 24 & 63 & 128 & 49 & 166 & 141 & 145 & 181 & 42 \end{matrix}\right] & \begin{matrix} p_{11} \\ p_{11d} \\ p_{11l} \\ R_{11p} \\ R_{11m} \\ R_{11s} \\ CB_{11p} \\ CB_{11m} \\ CB_{11s} \\ \\ \\ \end{matrix} \\ \begin{matrix} t_{11r} & t_{11l} & t_{11cr} & t_{11cl} & t_{11Rr} & t_{11Rl} & t_{11p} & t_{11m} & t_{11s} \end{matrix} & \end{array}$$

$$\underline{\Gamma}^+ = \begin{array}{cc} \left[\begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 16 & 37 & 42 & 63 & 87 & 100 & 93 & 106 & 126 \\ 23 & 63 & 127 & 50 & 181 & 155 & 133 & 163 & 44 \end{matrix}\right] & \begin{matrix} p_{11} \\ p_{11d} \\ p_{11l} \\ R_{11p} \\ R_{11m} \\ R_{11s} \\ CB_{11p} \\ CB_{11m} \\ CB_{11s} \\ \\ \\ \end{matrix} \\ \begin{matrix} t_{11r} & t_{11l} & t_{11cr} & t_{11cl} & t_{11Rr} & t_{11Rl} & t_{11p} & t_{11m} & t_{11s} \end{matrix} & \end{array}$$

and the initial marking of the new redundant PPN system is

$$\underline{S}_H[0] = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 9\ 11]^{\mathrm{T}}.$$

We now follow the evolution of the PPN model associated to the protection system 11. Assume that downstream current direction is detected, so that transition t_{11r} fires. The signal of the current direction is detected by the control center that calculates the state of the system to be

$$\underline{S}_f[1] = [0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 3\ 10]^{\mathrm{T}}.$$

Furthermore, assume that the current is recognized as overcurrent, and transition t_{11Rr} fires, making the relay ready to trip. The control center assesses the following state of the PPN:

$$\underline{S}_f[2] = [0\ 0\ 0\ 1\ 1\ 1\ 0\ 0\ 0\ 22\ 25]^{\mathrm{T}}.$$

In this state, the three unitary values in correspondence of the places $R_{11m}, R_{11p},$ and R_{11m} indicate that the relay is sensing the current fault and a trip command must be sent to the circuit breaker. Now, when main relay 11 sends the trip signal to the corresponding circuit breaker (fires transition t_{11m}), the switch fails to operate. The control center receives the trip signal but is not informed about the main circuit breaker status and no token is deposed in the place CB_{11m}, so it can deduce that a postcondition fault occurs. The perceived state of the system becomes

$$\underline{S}_f[3] = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ -104\ -156]^{\mathrm{T}}.$$

At this point, the primary relay can operate, transition t_{11p} fires, and the final state of PPN 11 becomes

$$\underline{S}_f[4] = [0\ 0\ 0\ -1\ 0\ -1\ 1\ 0\ 0\ -116\ -168]^{\mathrm{T}}.$$

In order to detect failures, the control center evaluates the syndrome vector via $[-\underline{C}^*\ \underline{I}_2] \cdot \underline{S}_f\ [4]$

$$\underline{S}_P = [-\underline{C}^* \quad \underline{I}_2] \cdot \underline{S}_f[4] (\mathrm{mod}\ 13) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\underline{S}_T = [-\underline{C}^* \quad \underline{I}_2] \cdot \underline{S}_f[4] = 13 \times \begin{pmatrix} 8 \\ 12 \end{pmatrix} \neq \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

By inspecting matrix D, the eighth column corresponds to the syndrome vector s_T. Therefore, the reasoner can deduce that a postcondition (transition) fault has occurred and a data transmission to the control center was erroneous (because the eighth column of D corresponds to the main relay of protection system 11). The same procedure is repeated for protection systems 10 and 12, but no anomalies are found. When this phase ends, the position of the fault can be determined by using the third procedure. Note that the scheme described in this section requires that t_{11r}, t_{11Rr}, and t_{11m} are observable transitions (so that they can drive the token changes in the redundant places) and that the state of $p_{11}, p_{11r}, \ldots, CB_{11p}, CB_{11m}, CB_{11s}$ eventually becomes available. Both of these requirements are satisfied in this example.

In the aforementioned discussion, we did not take into account two typical phenomena in electrical systems: uncertainty about the measurement data and the noise that can be added to any signal sent or received via the communication system. Our approach has assumed that action against such uncertainty (measurement/noise) is taken individually (by each sensor or receiver) using some type of threshold rule, so that eventually, discrete information is obtained at the control center (e.g., a transition has fired or a circuit breaker has opened). Once

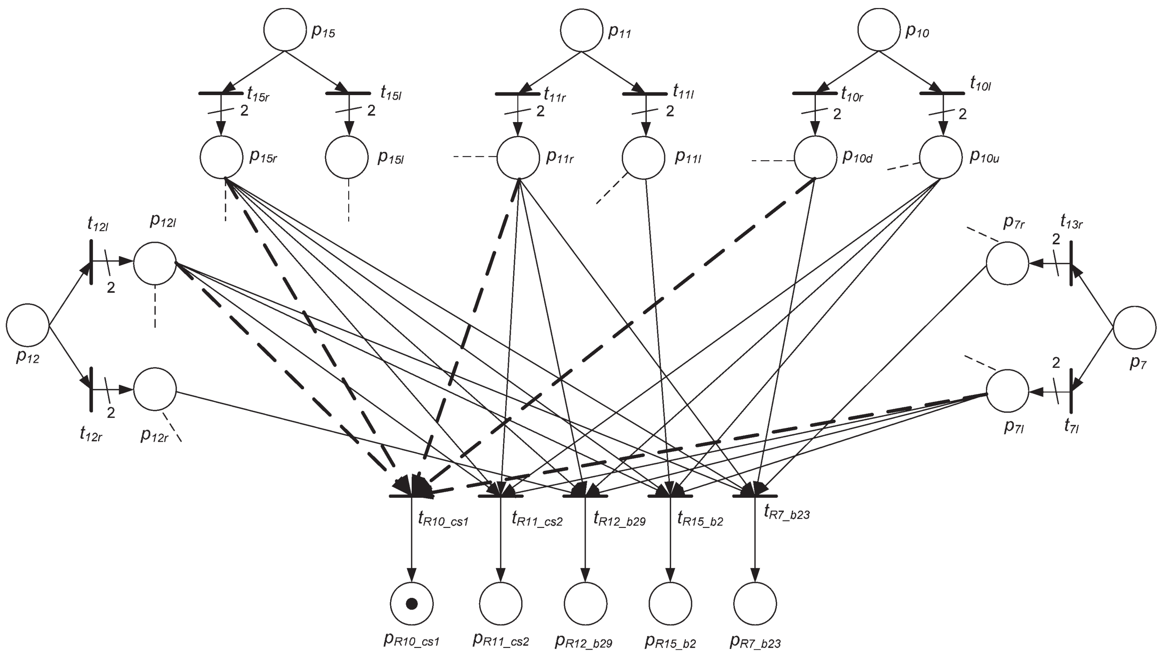

Fig. 7. PN model for radial distribution system of case 2.

this thresholding is accomplished at the sensor/receiver level, any errors due to the uncertainty and the noise are processed automatically by the proposed diagnosis algorithm, as long as the failure detection strategy is designed to be robust to the resulting error. The presented case study and the next one highlight the insensitivities to noisy measurement or uncertain data.

Furthermore, it is noted that the introduced delay to provide information to the reasoner is not critical. In fact, the operations of fault detection and localization require execution times that are perfectly compatible with the classical delays introduced by communication systems. However, an excessive delay is implicitly processed automatically by the system, as it is recognized as "information not received" from the control center or as misoperation of protection systems.

B. Scenario 2

In this case, a three-phase fault is supposed to occur at section $cs2-cs1$, on the link between the two cs's (between feeders E and D). The protective relays $R12$, $R11$, and $R7$, with their corresponding circuit breakers $CB12$, $CB11$, and $CB7$, have responded to the fault, and the information is communicated correctly to the control center. The fault position can be detected by analyzing the evolution of the PN model shown in Fig. 7, where only the connections to the fault transitions are considered (refer to Section IV-C). The final state of the PN contains a token in place p_{R10_cs1}, and we conclude that, even though relays and circuit breakers have operated correctly, there were incorrect trips: Not all loads connected to feeder E have been unsupplied. A correct coordination among relays could have minimized the disservice because relays $R10$ and $R7$, and their CBs would have tripped.

Any network topology changes, due to planning or operational needs (e.g., reconfiguration), are adequately addressed by the introduced method that allows a high degree of modularity in the composition of the PNs. The possible situations can be classified in three cases. 1) In the new network topology, the placement of the protection systems and the direction of the short-circuit currents do not change. 2) In the new network topology, the placement of the protection systems does not change, but the direction of the short-circuit currents changes. 3) The new network topology changes the placement of the protection systems. In the first case, the PN designed before the topology changes occur does not change, and in the second case, only the connections between places p_{pd} and p_{pu} (status of "evaluation of current direction") and PLFs must be changed, but without altering the number of places and transitions; in the latter case, we must take into account the introduced (removed) protection systems by adding (removing) new PPNs to connect (disconnect) to PLFs.

It is noted that, as regards the two presented case studies, generally, it is not possible to associate a data transmission error to a transition fault and a false trip error to a place fault; this has been confirmed by further simulations with different systems, not presented in this paper.

VI. Conclusion

This paper has developed a new model for smart grids in order to be able to rapidly perform fault diagnosis despite erroneous data transmissions. The approach is based on PN theory applied to a carefully developed PN model of the underlying network topology under test. The design of the PN model has been carried out in a modular fashion by composing PN models for individual protection systems along with current detectors. The presented method is capable of dealing with distribution systems with DG, which typically present challenges including false tripping due to coordination loss of protection devices. The method has been validated by means of a case study on a typical radial distribution network, composed of different protection devices that require complex coordination. In particular, the effectiveness of the method has been demonstrated by means of two case studies related to protection systems and DG. From our study, we conclude that the proposed method can remove a lot of complexity in data analysis and allows quick assessment of information while avoiding cascading failures in power system protection.

Clearly, the application of this method favors the creation of a smart grid but requires new investment in ICT and protection systems. From an industrial point of view, the technical feasibility of the proposed solution requires the development of appropriate software and adjustments of protective systems. Currently, incremental investments appear distorted as a result of insufficient decoupling of the industry, and network operators have few incentives to develop the grid in the overall market interest [34]. Nevertheless, considering that both the U.S. and the European Union have planned significant investment for distribution networks [5], [34], the proposed detection strategy is consistent with current trends and directives.

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