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DG and Protection Systems in Distribution Network: Failure Monitoring System based on Petri Nets

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Abstract

The paper deals with the problems that can rise in protection systems of the distribution networks in presence of Distributed Generation (DG). A mathematical formalism is introduced to model protection trip problems in radial distribution networks and a procedure to monitor failures of the protection systems based on Petri Nets and a simple matrices manipulation is presented. Such procedure allows designing a tool for a centralized monitoring system of a power protection scheme. In the paper also an architecture to support the tool is proposed and two case studies are simulated on a real Italian distribution network. The proposed approach represents an interesting solution to improve reliability into distribution systems in presence of DG.

Introduction

The growing public awareness for continuous energy consumption, more and more competitive supply markets and technology developments in power systems, is increasing the interest in Distributed Generation (DG). The spread of DG is also encouraged by the national and local regulation evolution that favours and supports the penetration of both cogeneration and renewable energy sources, also by means of faster procedures for licenses and permits [1].

This prefigures a presence of DG in distribution systems approximately up to 20% of the total energy resources between 2010 and 2020. Nevertheless, a high penetration level of DG may create technical and reliability problems [2-3]. In particular, several studies demonstrated that a widespread use of DG could significantly contribute to increase fault current levels and to introduce reverse power flow along the network, leading to coordination and setting problems of the overcurrent systems [4-7].

In this scenario, in order to ensure safe and reliable operations, more precautions are required and new tools to support the operators in monitoring of protection systems are expected. In fact, even though many data in power distribution system can be managed automatically by lower levels, a lot of alarms implies human supervisor to individuate misoperations in protection system and to decide the type of intervention.

In the past, two main topics were handled regarding both to support operators in decision phase and to replace the role of the failed relays. In particular, as regards the first topic, in [8] the authors developed an industrial strength multi-agent system (MAS) that integrates a number of legacy intelligent systems for analyzing power system data as autonomous intelligent agents. In [9-10] other two examples of MAS technology was shown, highlighting the flexibility and the extensibility it offers. Knowledge-based systems to extract the relevant information from SCADA system data had been presented in [11]. Regarding the second topic, in [12] an integrate scheme to study power system vulnerability in presence of protection failures was considered and a reliability system based on stochastic properties was tested. The same problem was handled in [13], illustrating the expected reliability benefits by inclusion of monitoring and self-checking facilities within relays.

Nevertheless, the proposed solutions don't consider the presence of DG and relay failure due to miscoordination of protection systems. So, in this paper the problem of wrong trips of the protection system on distribution network in presence of DG is handled and a monitoring strategy, based on a Petri Net, is introduced. Petri net is a powerful tool, enabling users to graphically design and monitor complicated process-based activities in a simple, yet comprehensive, manner. The use of Petri nets offers potential advantages in system modeling and analysis, especially in terms of the distributed representation of the system state and of the ability to represent coupling of system components by means of common places.

The proposed approach is based on a central controller that identifies and locates failures in order to support Distribution Network Operator (DNO) to monitor failures or wrong operations of protective devices. The procedure is based on an algebraic approach for centralized fault identification in discrete event systems and it is developed using Galois Fields (GF). Such a procedure has been already applied in power system field for more general power system monitoring problems with success.

The paper is organized as follows: Section II discusses the overall problem and presents an analytical

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formulation; Section III introduces the procedure to solve the introduced problem; in Sections IV the protection system is modeled by Petri net and in Section V the solution method is presented. An architecture to support the theoretical solution is proposed in Sections VI while Section VII presents two case studies; Section VIII provides concluding remarks.

Problem formulation

The trip protection problem in presence of DG has been modeled for a radial network with n lines, m buses and $N = N_1+N_2+\ldots+N_n$ generators, where N_k is the number of generators on the line k. An example is illustrated in figure 1.

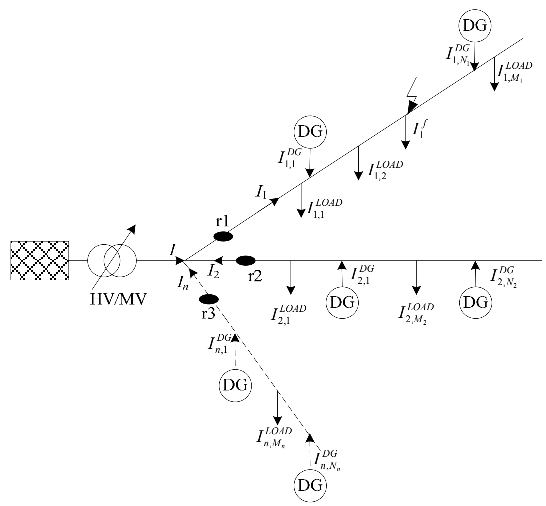

Fig. 1: Protections in Radial Networks with DG

If a fault is present on the line k with a fault current equal to I_k^f, considering the current references shown in figure 1, the current balance on the line k is the following:

$$I_k = I_k^f - \sum_{i=1}^{N_k} I_{k,i}^{DG} + \sum_{j=1}^{M_k} I_{k,j}^{LOAD} \qquad (1)$$

where I_k is the current that flows through the protection r_k of the line k, $I_{k,i}^{DG}$ is the current injected on the line k by i-generator, $I_{k,j}^{LOAD}$ is the current absorbed from the line k by j-load in presence of load and M_k is the number of loads on the line k. So, considering the amplitudes, the relay r_k trips if

$$I_k > I_k^{th} \quad \Rightarrow \quad \left| I_k^f - \sum_{i=1}^{N_k} I_{k,i}^{DG} + \sum_{j=1}^{M_k} I_{k,j}^{LOAD} \right| > I_k^{th} \qquad (2)$$

where I_k^{th} is the current threshold of the relay r_k.

In order to have a correct trip on the line h, the condition will be:

$$I_h < I_h^{th} \quad \Rightarrow \quad \left| \sum_{i=1}^{N_h} I_{h,i}^{DG} - \sum_{j=1}^{M_h} I_{h,j}^{LOAD} \right| < I_h^{th} \qquad (3)$$

Procedure for monitoring and failures detection

In order to monitor correct grid operations in presence of fault, the procedure shown in figure 2 is proposed.
The procedure is based on a continuous evaluation of the fault vector

$$\underline{I}^f = \left(I_1^f \quad I_2^f \quad \ldots \quad I_n^f \right)$$

If it is different from zero, a procedure to individualize the fault starts. In the following comparison, the inequality (2) and (3) are evaluated: if at least one is false, the monitoring procedure to localize wrong trips begins. The individuation of relay misoperation, carried out according to a careful tool, will be presented in the following section.

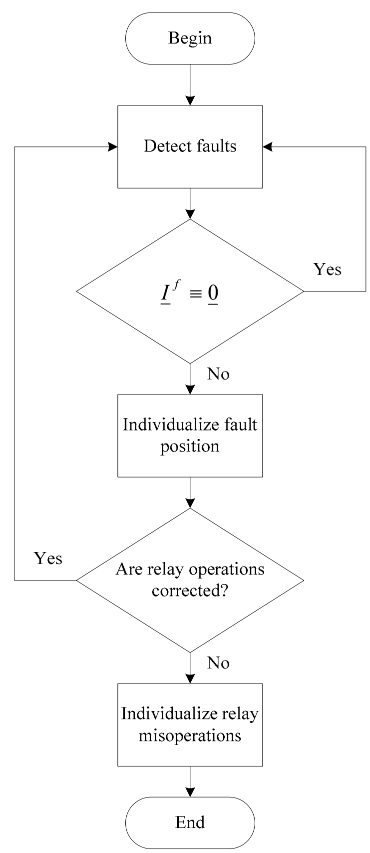

Fig. 2: Flow chart for the monitoring system

Petri net modeling of power system protection

The wrong operations of overcurrent relays are detected applying a method based on Petri Nets and the concepts of place failure and transition failure described in [14].
In order to explicit the method, a model of power system protection system is presented.
In particular, the model regards one relay equipped with circuit breaker and the behaviour of the protected line. The model can be replied for other relays which aren't correlated in protection operations among them, equipped with a circuit breaker that protects power lines.
In figure 3, the marked Petri net models an overcurrent relay and the protected line. The place p_1 corresponds to the condition of absence of fault on the line, p_2 to the condition that the relay is able to sense the fault, p_3 models that the relay is set, p_4 the presence of a fault on the line, p_5 the trip signal is sent, p_6 the fault is isolated, p_7 the system is ready for assuming the initial state and p_8 summarizes the relay tripped. As regards with the transitions, t_1 models the occurrences of a fault on the line, t_2 the response of the relay, t_3 the opening of the correspondent circuit breaker, t_4 the fault clearance, t_5 the resetting of the relay and t_6 the recovery of the system.

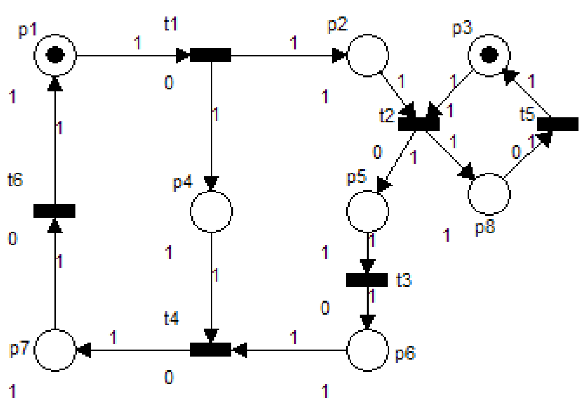

Fig. 3: Petri net model for protection system

The initial marked Petri net indicates that the relay is ready to sense a fault (token in p_3) and the system operates correctly (token in p_1). If a fault occurs, the correct evolution of the Petri net is shown in figure 4, until the restoration of the service. The movement of tokens throughout the Net models the execution of the operations.
From the analysis it can be noted that the Petri net is limited, reversible and lively but for the aim of the work the most important behaviour property is the conservativeness. In other words if the Petri net is conservative, fault places or fault transitions don't occur.

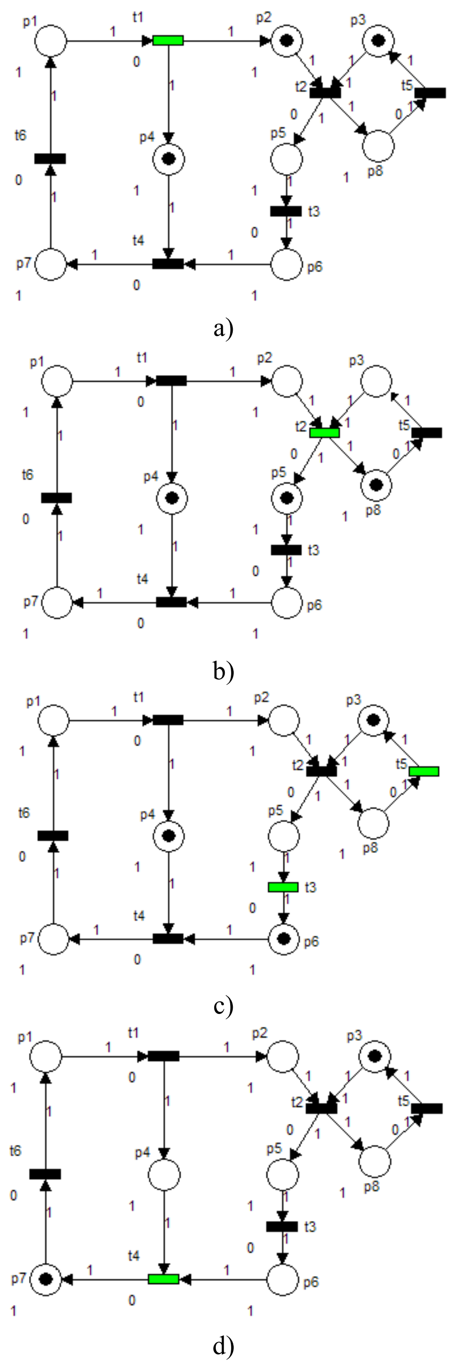

Fig. 4: Correct evolution of the Petri net

Method for failure relay detection

In order to detect wrong trips of the protection system the analytical method illustrated in [14] will be used.
It is based on the concepts of transition failure and place failure. A transition failure takes place if transition t_j fires and no all tokens are deposited to output places even though tokens from the input places have been used (*postcondition failure*). If the tokens which were

supposed to be removed from the input places of the faulty transition are not removed, a *precondition failure* has happened. Precondition and postcondition failures can be modeled by means of two vectors $\underline{e}_T^+$ and $\underline{e}_T^-$ respectively, with dimensions bx1 and composed by elements of $\mathbb{N}$, where b is the number of the places of the Petri Net.

In particular, the j-entry of $\underline{e}_T^+$ or $\underline{e}_T^-$ indicates the number of postcondition or precondition failures on the correspondent transition. So, the state after a transition fault becomes:

$$\underline{C}_f[k] = \underline{C}[k] - \underline{P}^+ \cdot \underline{e}_T^+ + \underline{P}^- \cdot \underline{e}_T^- \qquad (4)$$

where $\underline{C}_f$ is the Petri Net state reached after transition fault, $\underline{C}$ is the state, at the same epoch, without faults, $\underline{P}^-$ and $\underline{P}^+$ are the matrices that specify the arcs from places to transitions and the arcs from transitions to places.

A place failure takes place if the number of tokens in the place is corrupted. In terms of equations, a place failure at the epoch k produces a wrong value of the marking vector $\underline{M}$. Place fault can be expressed by a vector $\underline{e}_P$ with dimensions lx1 and composed by elements of $\mathbb{Z}$ where l is the number of the transitions of the Petri Net. So the state after a place failure becomes:

$$\underline{C}_f[k] = \underline{C}[k] + \underline{e}_P \qquad (5)$$

It can be noted that the place corruption can happen adding or subtracting tokens in a place, so the elements of $\underline{e}_P$ can be positive or negative. Combining equations (4) and (5) both failures can be considered:

$$\underline{C}_f[k] = \underline{C}[k] - \underline{P}^+ \cdot \underline{e}_T^+ + \underline{P}^- \cdot \underline{e}_T^- + \underline{e}_P \qquad (6)$$

The fault diagnosis is performed considering the syndrome vector for transition $\underline{s}_T[k]$ and place fault $\underline{s}_P[k]$

$$\begin{cases} \underline{s}_T[k] = \underline{D} \cdot \underline{e}_T \\ \underline{s}_P[k] = [-\underline{G}^* \quad \underline{I}_d] \cdot \underline{e}_P = [-\underline{G}^* \quad \underline{I}_d] \cdot \underline{M}_f \end{cases} \qquad (7)$$

where I_n is a bxb identity matrix, G^* and D are a dxb integer matrix and a dxl integer matrix to be designed according the rules of [14]. $\underline{M}_f$ is the marking net vector after the failure. In (7) if $\underline{s}_T[k] \neq 0$ and/or $\underline{s}_P[k] \neq 0$ transition or place faults have taken place.

The procedure for detecting and identifying mixed transition and place faults is based on the operations in Galois Field GF(q), where q is a prime number.

Architecture for monitoring power system

In a power system data power flow and executed operations are controlled by means of a hierarchical system consisting of a top level in which the operators interact with ECC (Energy Control Center), by means of HMI (Human Machine Interface), computers and a field level with a distributed data acquisition, pre-elaboration and transmission system. As in power system a lot of changes occurs, many data, in form of alarms, are sent to ECC in order to analyze them and propose suitable management actions. Usually, alarms regard operation of breakers, excursion of different monitored variables and misoperation of installed components.

The proposed solution, that supports the monitoring and diagnostic operations in ECC, is based on a standard architecture consisting of SCADA (Supervisory Control and Data Acquisition) system, EMS (Energy Management System) and RTU (Remote Terminal Unit). In particular, ECC is equipped with SCADA system and EMS, while the measurement and acquisition points (MAPs), of the field level, are equipped with RTU. ECC and MAPs exchange analog and digital data in real time, loading them in a database. Analog data are active and reactive power, voltage, frequency and current while digital data are the status of switches on the network. In order to deal with analog signals, each RTU is equipped with ADC (analog to digital converter) and the front-end processor (FEP) with DAC (digital to analog converter). Data acquired by RTU are sent to next level using power line carrier communication (PLCC). The architecture of the system is shown in figure 5.

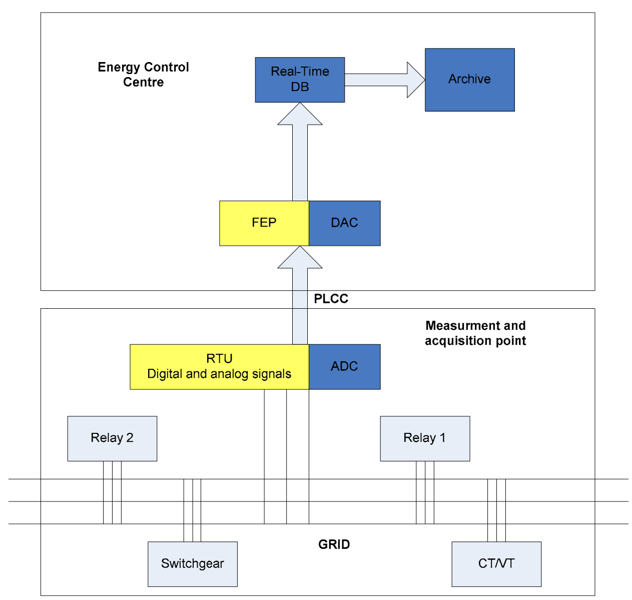

Fig. 5: Architecture for monitoring power system

If during the correct operation of the power distribution system a change of status occurs (fault, trip of relay etc.), signals are sent to ECC and data are collected into a real time database. The Petri net structure models protection system and provides a simulation environment of the network for several inputs. It is uploaded on computers of ECC, where a collection of static structures, places and transitions, describes the sequence of events and control the status of the operation by monitoring the data from switches and sensors distributed on the power network. The signals from inputs are compared with levels defined in the transition and place structure and the operator in ECC is informed step by step about the current status of the network and can made decisions in case of misoperation of the system.

Case study

In order to illustrate the presented procedure two case studies are considered. They handle two typical problems in distribution power system due to DG and inadequate setting or coordination of the protection systems. The considered network with its protection system is a real distribution grid located in Sicily (Italy), with protection relays installed at the beginning of each line. At present, overcurrent protection relays are set according to DK 4452 standard [15]. In particular, a current direction insensitive relay, with three different current thresholds, protects the feeder (PFeeder) and two current direction insensitive relays, with two different current thresholds, protect each line (PLine). While PFeeder is characterized by two delayed current thresholds and one in time base, PLine by one delayed current threshold and one in time base. In figure 6, the network layout, the arrangement of protection relays and the trip curves of the relays are shown.

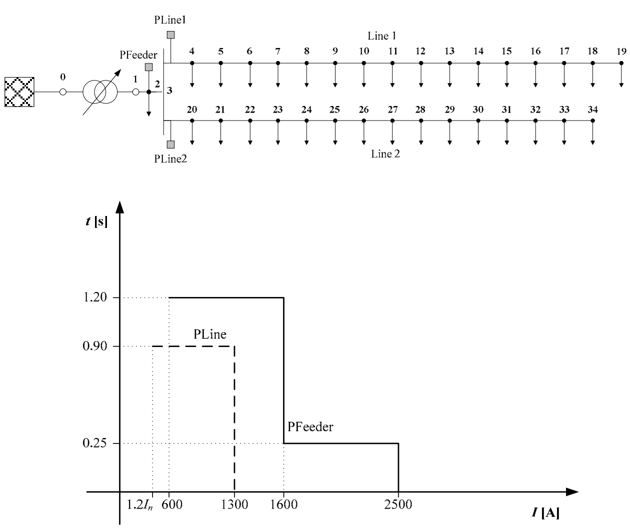

Fig. 6: Test network and trip characteristics of the relays

A. Case 1

Considering a three phase fault between bus 4 and bus 5, when a distributed generator with rated equal to 100% of the load is connected at the bus 20, tripping protection problems rise. The fault current is 4880 A and flows in the relay 1, a current of 2685 A flows in relay 2 due to generator contribution, a current of 2195 A comes from HV/MV substation. In such a situation, considering the trip relay characteristics, a wrong trip of relay 2 happens, disconnecting line 2. The situation is shown in figure 7. A similar situation can be verified in presence of an overload on the line 1.

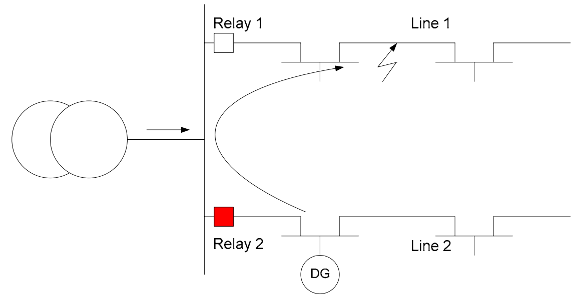

Fig. 7: Wrong trip of overcurrent protection

It can be noted that the inequality condition (3) is not verified.

B. Case 2

Considering a line-to-line fault between bus 33 and bus 34, when a distributed generator with rated equal to 15% of the load is connected at the bus 20, the relay 2 doesn't trip after the fault. In fact, while the fault current is 5200 A, the contribute of the generator is 3900 A and the current that flows in relay 2 is 1300 A. As the current threshold for polyphase fault is 1300 A, the protection could not trip. The situation is shown in figure 8.

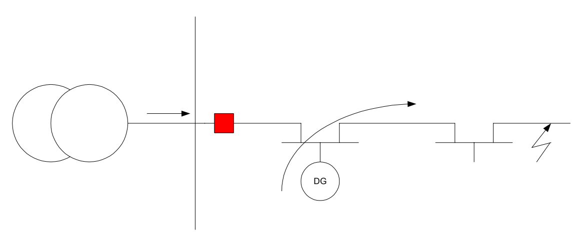

Fig. 8: Wrong trip of overcurrent protection

Also in this case, it can be noted that the inequality condition (2) is not verified.

C. Results

In order to monitor the two wrong protection power system operations, the presented Petri net scheme was used and the diagnostic procedure exposed in section IV was applied.

In the case 1, by evolving of the Petri Net scheme, the conservativeness of the Petri net is lost. In particular, the transition t_1 fires because relay senses a fault current due to the generator fault contribution, even though there aren't faults on the line 2. So, the token in place p_4, indicating the presence of faults, is "lost" and the sensor doesn't send any signal to ECC. The new wrong marked Petri net, after the fired transition t_1, is shown in figure 9.

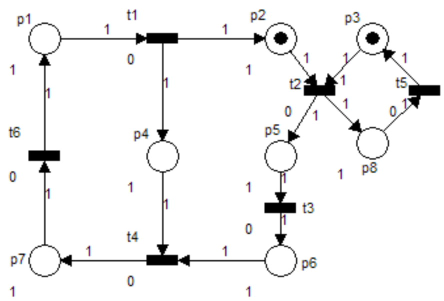

Fig. 9: Marked Petri net for line 2 and relay 2 after t_1 in case 1

In order to individualize the place fault, two added places where considered ($d = 2$), with $l = 6$ and $b = 8$, the prime number was $q = 11$. The matrix D^*, obtained in GF(11), was:

$$\underline{D}^* = -q \cdot \underline{D} = \begin{pmatrix} -11 & -22 & -33 & -44 & -55 & -66 \\ -11 & -44 & -99 & -55 & -33 & -33 \end{pmatrix}$$

A primitive element of GF(11) is 2, so the designed matrix $\underline{H}_d$ is:

$$\underline{H}_2 = \begin{pmatrix} 3 & 6 \\ 9 & 3 \end{pmatrix} \cdot \begin{pmatrix} 3 & 7 & 7 & 8 & 3 & 9 & 8 & 9 & 1 & 0 \\ 6 & 6 & 10 & 1 & 3 & 10 & 3 & 4 & 0 & 1 \end{pmatrix} = \underline{\Phi} \cdot [\underline{G} \quad \underline{I}_2]$$

where I_2 is a 2 x 2 identity matrix.

The initial marked Petri net, considering the added places, and the initial state without added places $C_0 = [1\ 0\ 1\ 0\ 0\ 0\ 0\ 0]^T$, is:

$$\underline{C}_H[0] = \begin{bmatrix} \underline{I}_8 \\ \underline{G}^* \end{bmatrix} \cdot \underline{C}[0] = [1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 12 \quad 6]^T$$

where I_8 is a 8 x 8 identity matrix and

$$\underline{G}^* = q - \underline{G} = \begin{pmatrix} 8 & 4 & 4 & 3 & 8 & 2 & 3 & 2 \\ 5 & 5 & 1 & 10 & 8 & 1 & 8 & 7 \end{pmatrix}$$

The identification of the place fault was carried out considering the second equation of (7) with:

$$\underline{e}_P = [0 \quad 0 \quad 0 \quad -1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$$

After the transition t_1 the marked Petri is:

$$\underline{C}_f[1] = [0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 11 \quad 16]^T$$

So, syndrome vector for place fault becomes:

$$\underline{s}_P[1] = [-\underline{G}^* \quad \underline{I}_d] \cdot \underline{C}_f[1]$$

$$\underline{s}'_P[1] = \underline{\Phi} \cdot \underline{s}_P \bmod(11) = \begin{pmatrix} 3 \\ 2 \end{pmatrix}$$

By inspecting matrix $\underline{H}_2$ the place p_4 fault is easily identifiable with wrong number of token -1. In fact, multiplying by -1 the fourth column in mod(11), the same value of syndrome is reached. Vice versa transition faults aren't present because the error syndrome is equal to 0.

So, as the place p_4 is associated with the presence of a fault, the relay can trip, firing transition t_2, without a real fault on the line.

In the case 2, a place fault happened again. In fact, even though t_1 fires, no token is moved to p_2 because the relay doesn't send any signal to ECC.

In particular, considering the vector:

$$\underline{e}_P = [0 \quad -1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

after the transition t_1, the marked Petri net is:

$$\underline{C}_f[1] = [0 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 11 \quad 16]^T$$

and

$$\underline{s}'_P[1] = \underline{\Phi} \cdot \underline{s}_P \bmod(11) = \begin{pmatrix} 9 \\ 7 \end{pmatrix}$$

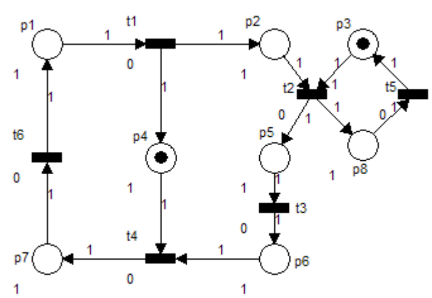

Fig. 10: Marked Petri net for line 2 and relay 2 after the t_1 in case 2

So, by inspecting matrix $\underline{H}_2$ wrong tokens are in the place p_2. Such a Petri condition didn't allow the action of the relay because there weren't sufficient tokens to fire transition t_2, even though the fault was present (token in

p_4). The situation after the first transition is shown in figure 10.

Conclusion

The paper presented a method based on Petri Net able to support operators for monitoring protection systems in power distribution network, in presence of distributed generation. Using Petri-net approach a graphical representation of any logical process has been produced.
In order to formalize the problem, a suitable mathematical model for fault analysis has been introduced and the procedure to implement the monitoring system was based on an algebraic approach that considers Galois fields and the manipulation of simple matrices.
Furthermore, the proposed physical architecture, that supports the Petri scheme, is able to provide reliable information exchange among various entities in the system and its distributed nature can reduce the burden on the higher level computer systems through data aggregation.
In the paper two applications, related to protection distribution systems, have been considered showing that the proposed scheme removes a lot of complexity in data analysis, offering the potentiality for a tool able to manage few information avoiding cascading failures in power system protection.
With advantage, the developed system can be used to provide a history of events that lead to any particular failure.
Further development could be made modeling communication devices into Petri scheme in order to help electric utilities to achieve their goals of providing reliable energy service.

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