Fault Diagnosis on Electric Power Systems based on Petri Net Approach[1]

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1. Introduction

Fault diagnosis is a process that identifies and locates faults occurrence in systems using their inputs, outputs, and their structures. In the context of electric power systems fault diagnosis is realized using the voltages and currents measurements at each node and the physical connections. In this process, there are two conventional important problems that must be solved: 1) how to determine whether a system is diagnosable and 2) how to design a diagnoser. The problem of fault diagnosis has been addressed through various approaches and application methods, for example based on artificial intelligence techniques, and based on Discrete Event Systems. In the last approach, Finite Automata and Petri nets have been mainly used as modelling formalism.
Although the Finite Automata are suitable for Discrete Event Systems, its application is limited to small systems, since the models should explicitly taken in account all the possible states of the system, resulting in very large models which are very difficult to work with them. In order to cope with the state explosion problem, the structural models, represented as vector Discrete Event Systems or Petri nets allow a compact representation of a Discrete Event Systems, avoiding a large set of states as Finite Automata does. Also, with this formalism, the discrete event systems analysis can be realized using linear algebra methods. Using the advantage of these features, fault diagnosis has been addressed using Petri nets.
Several methods have been proposed recently, for example in (Sheng-Luen et al., 2003) and (Genc & Lafortune, 2003) the Petri nets approach is used, but the diagnosability test has been based on the reachability graph; thus the method is limited to small size systems (Sampath et al., 1995) and (Sampath et al., 1996). In (Lefebvre & Delherm, 2007) a diagnoser based on the Petri nets paths and causality relationships is proposed to determine the presence of faults in a system. In (Hadjicostis & Verghese, 1999a), (Hadjicostis & Verghese, 1999b) and (Hadjicostis & Verghese, 2000) Petri nets model is used in order to introduce

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redundancy into the system that allow to detect and isolate faults. Unfortunately, all those solutions have the state explosion problem.

In order to cope with the state explosion problem, in (Ramírez-Treviño et al., 2004), (Ramírez-Treviño et al., 2007) and (Ruiz-Beltrán et al., 2007) techniques based on structural characterizations for determining the diagnosability property are proposed; in (Ruiz-Beltrán et al., 2007) is extended the characterizations and the diagnoser structures of (Ramírez-Treviño et al., 2004) and (Ramírez-Treviño et al., 2007), but that result is limited for binary Interpreted Petri nets. In these approaches, the diagnosability property is tested as a linear programming problem with polynomial complexity. In (Sheng-Luen et al., 2003), (Ulerich & Prowers, 1998), and (Yang et al., 2004) some applications of fault diagnosis using Petri nets are proposed, but they do not consider the diagnosability analysis of the system, which do not guarantee that a fault can be detected in a finite number of events when this fault occur. However, this condition is fulfilled in (Ramírez-Treviño et al., 2004), (Ramírez-Treviño et al., 2007), and (Ruiz-Beltrán et al., 2007).

Recently, the model-based approach for fault diagnosis in Discrete Event Systems is widely been worked by the research community of Discrete Event Systems. Several works on the matter use Petri nets for performing the fault diagnosis in electric power systems (Hadjicostis & Verghese, 1999a), (Hadjicostis & Verghese, 2000), (Ren et al., 2004), and (Ren & Zengqiang, 2006). In (Hadjicostis & Verghese, 1999a) and (Hadjicostis & Verghese, 2000) the authors propose coding theory techniques for detecting and locating failures in Discrete Event Systems in the field of electric power systems, they build a monitoring Petri net, which operates concurrently with the power network. However, for some failures, their techniques can not give a right explanation, and they do not determine how to construct the monitoring matrix. In (Ren et al., 2004), (Ren & Zengqiang, 2006) and (Proth et al., 1993) the same method is further studied. All possible failures are analyzed and remapped to the embedded Petri net models and a method of how to construct the monitoring matrix to encode the former Petri net model is proposed. However, the previous works do not determine the diagnosability of the electrical systems, i.e., it can not be determined off-line if a fault can be detected and located in a finite number of steps.

Based on the voltages and currents measurements and its digital processing with a relay to maintain the operation of the power electric system; in this chapter we will address: 1) how the operational behaviour of power electrical system with Interpreted Petri Net is represented, where the Interpreted Petri Net captures the normal and fault condition of the power electrical system. 2) How it is determined whether the model of the power electric system with Interpreted Petri Net is diagnosable and 3) how it is designed a diagnoser that has the same operative characteristics (security and velocity) that a relay in a real case. Thus, the results in (Ramírez-Treviño et al., 2004), (Ramírez-Treviño et al., 2007), (Ruiz-Beltrán et al., 2007) and (Santoyo-Sanchez et al., 2008) will be extended.

This chapter will be as follows. Section 2 will introduce fault features in electric power systems, how the electric power systems are modelled, and how the fault diagnosis is executed into the context of electric power systems. In the next section will be introduced a review Petri net notation and concepts used in the chapter. Section 4 will introduce the diagnostic from the Petri net point of view; in this case it is proposed a necessary condition to determine if a power electrical system is diagnosable. Moreover, it will be presented a method for designing a diagnoser, and how the diagnostic can be done. Next, in section 5 the results will be illustrated with a case study. Finally, in section 6 conclusions and future research will be given.

2. Fault modeling conditions in electric power systems

The analysis of the power electrical systems involve three stages namely, pre-fault condition (steady-state operation), fault condition (transient condition) and post-fault condition (how the network arrives to a new steady-state operation condition). If the relay is the equipment to protect the entire system, so it is necessary to know the exact relay behaviour under each stage. The tests of the relay performance are doing by off-line simulations; this reason renders necessary the modelling of the network components, the digital processing of the electrical signals and the procedure to take a logical decision: order a trip in a fault condition, do nothing in a safe condition. This decision is processed sample by sample. The relay behaviour, the used models to simulate the power electrical system network and the signal processing are described in order to clarify why and how Petri Nets are used to increment or to give redundancy to the protection schemes.

2.1 Relay behavior

The distance elements are the most widely used to protect transmission lines. Usually, they shared a communication channel to implement pilot schemes which increases the overall performance of the line protection. Each distance element has a boundary of the zone of protection in the locations of the currents transformers. The other boundary is extended in the forward direction and is determined by measurements of the system quantities that may vary with generation and configuration schemes. One of the most important design considerations of relaying is security. It is a measure of the relay's ability to avoid operation for all other conditions for which tripping is not desired. It is hard to achieve, and almost infinite variety of tests would be needed to simulate all possible conditions to which a relay may be exposed. Another important design consideration is protection velocity. The fault clearance must be as fast as possible for conditions within the transmission line. For distance elements is not a problem in their primary zone, but it is used to be a delay within an extended backup zone. This is shown in figure 1.

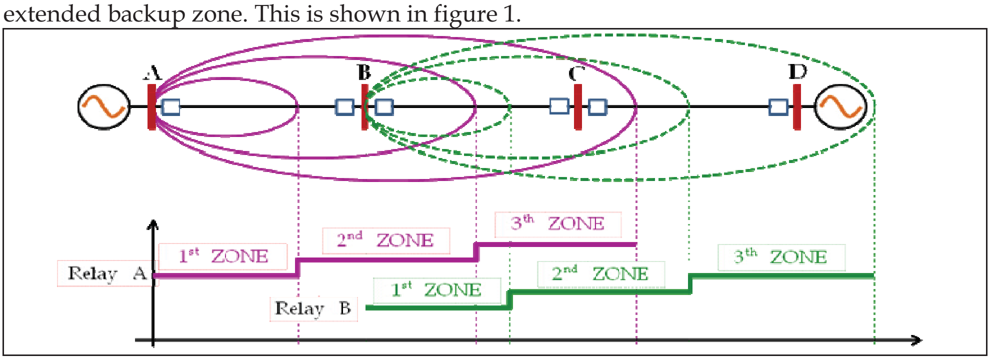


Fig. 1. Relay protection zones

Figure 2a shows the functional diagram of the distance relay. The process begins when the voltages and currents flow to the relay through the potential transformers and currents transformer installed in the power electric system network. These signals are passed through the relay's internal transducers, and then the signals are filtered before the analogical-digital conversion. The analogical filtering has the function of limit the bandwidth, so it is possible to use a low-frequency rate sampling without introduce a big error due to the aliasing phenomenon. The next step is the use of a digital filter to eliminate the superior harmonics and the no-periodic exponential component still remaining; the useful filters are the finite impulse response ones like the Fourier or cosine types.

Phasors of fundamental frequency (60 Hz) are computed by the discrete convolution between the digitalized, voltages (V) and currents (I), measured samples and the coefficients of the digital filter. It is demonstrated that independently of the frequency used rate in the analogical-digital conversion, the most convenient window length of the digital filter is equal to one period of fundamental frequency which means a delay of the trip, to fulfill the window with the fault signal, of one cycle the normal rate of relays is of 32 samples by cycle. The adjust parameters, to model short-circuits, are based in phasors which are used to represent the steady-state operation. Under ideal conditions, the estimate impedance is equal to the line section from the relay to the fault location. Faults provoke transient operation state in the network, so the impedance estimation is affected by the transient state components (fault resistance), this affects the relay response related with the fault detection in the limit zone operation (zone discrimination); for this reason the first zone of the relay is adjust to 80-90% of the protected line. Figure 2b shows the stages of the distance relay procedure and the normal consuming time each stage. Times are normalized with the fundamental frequency. In this figure, it could be notice that the execution of the digital filtering to compute the phasors of fundamental frequency is the most demanding time in the process of the trip signal. For typical filters the delay is one cycle of 60 Hz, the corresponding time is around 16.66 milliseconds. The delay of the digital filter is then a limitation that could not be avoided.

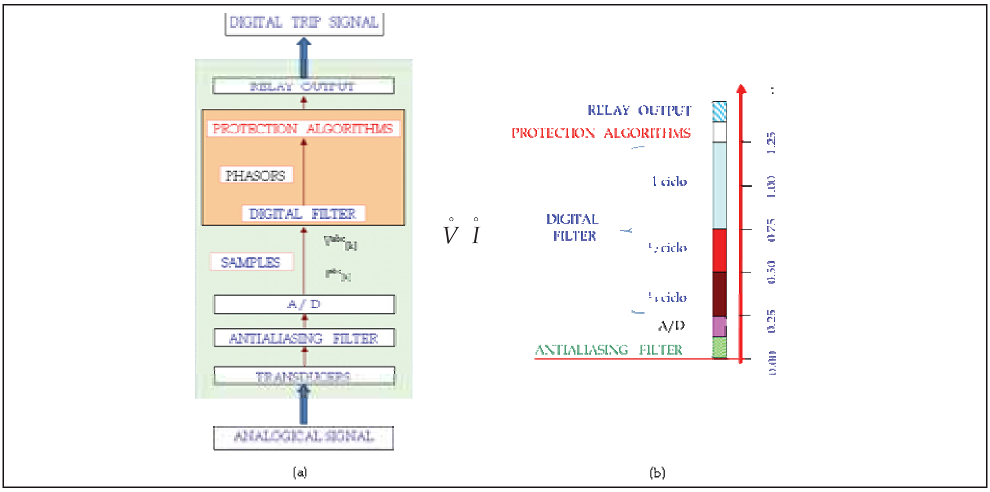


Fig. 2.a) Relay signal processing, b) Relay consuming times

The algorithms of the relay use both, phasors and the modal transformation described in section 2.2 of this document, here called symmetrical components; with this information the relay elaborate its response, the instantaneous one and the off-line one. The first involves the fault detection and the fault zone discrimination. The second is referred to the fault classification and localization.

· The relay detect a fault in its zone protection by comparing an adjust parameter with a function related with the voltages and currents phasors.
· The capacity to discriminate faults in front or behind near to the fault zone, is difficult because the estimate voltage phasor is almost zero; so, the effective and useful method is the polarization of the relay with the positive sequence network of the symmetrical components.
· The fault classification is performing by the symmetrical components as it is shown in table 1 described in section 2.2 of this document.
· The fault localization is computed by comparing the voltage-current relation with the total impedance of the line, so it is expressed in % of the line length.

National Electrical System is characterized by the large distance between the generation plants and the consuming points (charge). For that reason, the National Electrical System is divided into eight strategic located regional centers for operating and coordinating the production and distribution of the electric energy. Figure 3 shows the limits of each control area, also it is showed in this figure the electrical connectivity of the western control area which will be taken like an example, in this work, to implement the develop methodology. The fundamental criteria of reliability and operative security must be satisfied, so it is essential that must exists a good coordination among the operative entities in all operative stages. In this context these systems of energy generation have diverse exploration braches of study, among them, the maintenance area that as important factor as for costs, where innovating techniques of fault diagnosis for a later plan of reliable maintenance are required.

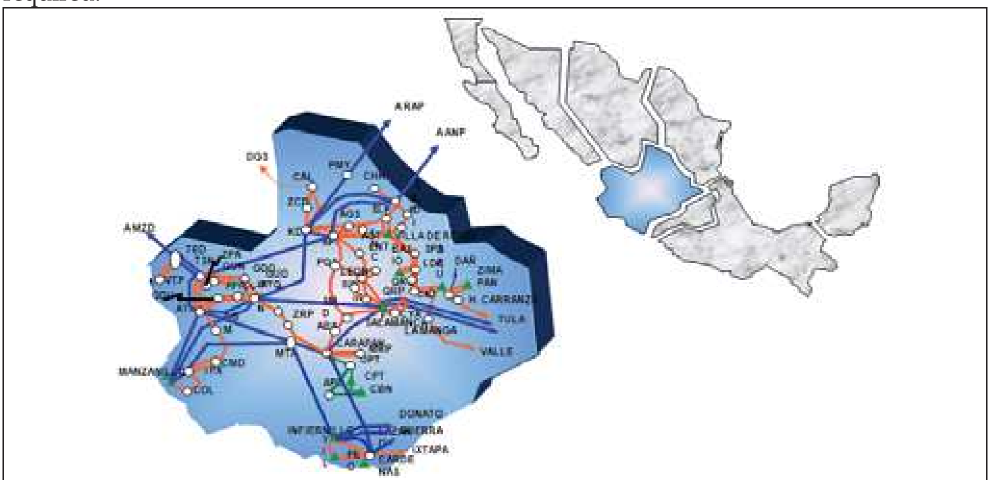


Fig. 3. Hierarchical level of control areas from Mexico and western area

2.2 Modeling the electrical system

The electrical systems are composed by generators that are interconnected through transmission lines to loads, sensors, capacitors, switches, substations, and transformers with the objective to produce and to distribute electrical energy. In order to simulate and analyze the electrical system behavior, the minimum models of elements of the system are: A) lines, B) sources and C) charges; which are brief described below. Figure 4 shows a piece of three phase line connected with a three phase source and a single charge each phase.

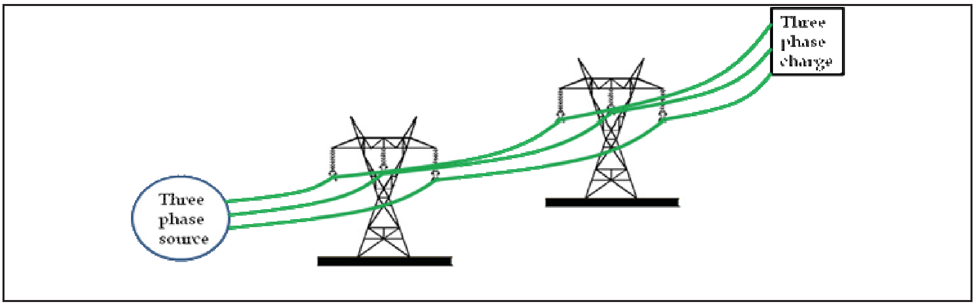


Fig. 4. Three phase line configuration

A) LINES

A rigorous analysis of the transmission line with losses is obtained by the Maxwell equations after some simplifications concerning to the electromagnetic field distribution. These simplifications conduced to the quasi-transversal electromagnetic fields. So, the line electromagnetic response of a transmission line is modeled by the Transmission Line Telegrapher's Equations as:

$$-\frac{\partial \mathbf{V}(x,t)}{\partial x} = \mathbf{R}(x)\mathbf{I}(x,t) + \mathbf{L}(x)\frac{\partial \mathbf{I}(x,t)}{\partial t} \quad (1)$$

$$-\frac{\partial \mathbf{I}(x,t)}{\partial x} = \mathbf{G}(x)\mathbf{V}(x,t) + \mathbf{C}(x)\frac{\partial \mathbf{V}(x,t)}{\partial t} \quad (2)$$

where $\mathbf{L}(x)$, $\mathbf{R}(x)$, $\mathbf{C}(x)$ and $\mathbf{G}(x)$ are the line per unit-length inductance, resistance, capacitance and conductance matrices, respectively.

The solution of these equations in frequency domain proceeds as follows; one has firstly the solution of the voltage and current like function of time and space as:

$$\mathbf{V}(x,t) = \mathbf{V'}(x,t)e^{j(\omega t+\varphi)} \qquad \mathbf{I}(x,t) = \mathbf{I'}(x,t)e^{j(\omega t+\varphi)} \quad (3)$$

If one has, $\mathbf{V}(x) = \mathbf{V'}(x)e^{j\varphi}$ and $\mathbf{I}(x) = \mathbf{I'}(x)e^{j\varphi}$ then;

$$\mathbf{V}(x,t) = \mathrm{Re}\left(\mathbf{V}(x)e^{j\omega t}\right) \qquad \mathbf{I}(x,t) = \mathrm{Re}\left(\mathbf{I}(x)e^{j\omega t}\right) \quad (4)$$

Substituting equation (4) into equation (1) and (2) yields to:

$$\frac{\partial\left(\mathrm{Re}\left(\mathbf{V}(x)e^{j\omega t}\right)\right)}{\partial x} + \mathbf{L}(x)\frac{\partial\left(\mathrm{Re}\left(\mathbf{I}(x)e^{j\omega t}\right)\right)}{\partial t} + \mathbf{R}(x)\left(\mathrm{Re}\left(\mathbf{I}(x)e^{j\omega t}\right)\right) = 0 \quad (5)$$

$$\frac{\partial\left(\mathrm{Re}\left(\mathbf{I}(x)e^{j\omega t}\right)\right)}{\partial x} + \mathbf{C}(x)\frac{\partial\left(\mathrm{Re}\left(\mathbf{V}(x)e^{j\omega t}\right)\right)}{\partial t} + \mathbf{G}(x)\left(\mathrm{Re}\left(\mathbf{V}(x)e^{j\omega t}\right)\right) = 0 \quad (6)$$

Solving these equations, one has:

$$\mathrm{Re}\left(e^{j\omega t} \frac{\partial \mathbf{V}(x)}{\partial x} \right) + \mathrm{Re}\left(\mathbf{L}(x)\mathbf{I}(x) \frac{\partial \left(e^{j\omega t} \right)}{\partial t} \right) + \mathrm{Re}\left(\mathbf{R}(x)\mathbf{I}(x) e^{j\omega t} \right) = 0 \tag{7}$$

$$\mathrm{Re}\left(e^{j\omega t} \frac{\partial \mathbf{I}(x)}{\partial x} \right) + \mathrm{Re}\left(\mathbf{C}(x)\mathbf{V}(x) \frac{\partial \left(e^{j\omega t} \right)}{\partial t} \right) + \mathrm{Re}\left(\mathbf{G}(x)\mathbf{V}(x) e^{j\omega t} \right) = 0 \tag{8}$$

Re-arranging equation (7) and (8) one obtains:

$$\mathrm{Re}\left(\left(\frac{\partial \mathbf{V}(x)}{\partial x} + \mathbf{L}\mathbf{I}(x) j\omega + \mathbf{R}\mathbf{I}(x) \right) e^{j\omega t} \right) = 0 \tag{9}$$

$$\mathrm{Re}\left(\left(\frac{\partial \mathbf{I}(x)}{\partial x} + \mathbf{C}\mathbf{V}(x) j\omega + \mathbf{G}\mathbf{V}(x) \right) e^{j\omega t} \right) = 0 \tag{10}$$

So, the real part is:

$$-\frac{\partial \mathbf{V}(x)}{\partial x} = \left(j\omega \mathbf{L} + \mathbf{R} \right) \mathbf{I}(x) \tag{11}$$

$$-\frac{\partial \mathbf{I}(x)}{\partial x} = \left(j\omega \mathbf{C} + \mathbf{G} \right) \mathbf{V}(x) \tag{12}$$

If $\mathbf{Z} = \left(j\omega \mathbf{L} + \mathbf{R} \right)$ and $\mathbf{Y} = \left(j\omega \mathbf{C} + \mathbf{G} \right)$, finally one obtains:

$$-\frac{\partial \mathbf{V}(x)}{\partial x} = \mathbf{Z}\mathbf{I}(x) \tag{13}$$

$$-\frac{\partial \mathbf{I}(x)}{\partial x} = \mathbf{Y}\mathbf{V}(x) \tag{14}$$

where $\mathbf{Z}$ represents the impedance series matrix, $\mathbf{Y}$ represents the admittance in derivation, both in per unit length and calculated like a linear function of the frequency (jω).

Treating the line like a simple circuit means neglecting the traveling time by taking into account the line length in the phase angle of each node (phase representation), one obtains the following equation (from equation (13)):

$$\mathbf{V}_{\phi} = \mathbf{Z}\mathbf{I}_{\phi} \tag{15}$$

For a geometric configuration of a common three phase horizontal line, if the line is constructed with the same material and has equal radius; additionally if it is positioned at a same height respect to ground and by assuming some simplifications like: equal coupling between conductors and homogeneous earth resistivity, it will conduces to the special case which has the following symmetry:

$$\mathbf{Z} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \tag{16}$$

This work makes special emphasis on the uses of the diagonalization methodology proposed in (Naredo et. al.,1987) to handle three phase systems like single ones. Using a modal transformation, for both voltage and current, one has:

$$\mathbf{V}_{\phi} = \mathbf{M}\mathbf{V}_{\mathrm{m}} \qquad \mathbf{I}_{\phi} = \mathbf{M}\mathbf{I}_{\mathrm{m}} \tag{17}$$

where $\mathbf{V}_{\mathrm{m}}$ and $\mathbf{I}_{\mathrm{m}}$ are called modal voltages and currents respectively and $\mathbf{M}$ is the modal transformation matrix.

By substituting equation (17) into equation (15), one obtains:

$$\mathbf{MV}_{\mathrm{m}} = \mathbf{ZMI}_{\mathrm{m}} \tag{18}$$

This process yields to:

$$\mathbf{V}_{\mathrm{m}} = \mathbf{M}^{-1}\mathbf{ZMI}_{\mathrm{m}} \tag{19}$$

It is demonstrated (Naredo 1992) (Strang 1998) (Greenspan D. & Casulli V., 1988) that the product $\mathbf{M}^{-1}\mathbf{ZM} = \Lambda$ lead to a diagonal matrix when it is used the self modes (eigenvectors of $\mathbf{Z}$), which is the required condition to treat the coupled three phase system like an uncoupled one. By using symmetrical components to diagonalizable this equation, which means by using

$$\mathbf{M} = \begin{bmatrix} 1 & 1 & 1 \\ a & a^2 & 1 \\ a^2 & a & 1 \end{bmatrix} \text{ and } \mathbf{M}^{-1} = \frac{1}{3}\begin{bmatrix} 1 & a^2 & a \\ 1 & a & a^2 \\ 1 & 1 & 1 \end{bmatrix} \tag{20}$$

then equation (19) is as follows:

$$\begin{bmatrix} V_m^+ \\ V_m^- \\ V_m^0 \end{bmatrix} = \begin{bmatrix} Z^+ & 0 & 0 \\ 0 & Z^- & 0 \\ 0 & 0 & Z^0 \end{bmatrix} \begin{bmatrix} I_m^+ \\ I_m^- \\ I_m^0 \end{bmatrix} \tag{21}$$

where $Z^+ = Z_8 - Z_m$, $Z^{-'} = Z_8 - Z_m$ and $Z^0 = Z_8 + 2Z_m$. Like these, the line coupled model could be solved like an uncoupled one, as:

$$V_m^+ = Z^+ I_m^+ ,\ V_m^- = Z^- I_m^- \text{ and } V_m^0 = Z^0 I_m^0 \tag{22}$$

B) SOURCES

The steady state solution yields to the following case, for example, if it is placed an ideal voltage source of 60 Hz, 115 kV line to line, in one end; modal voltages are (by definition $\mathrm{V}_{ab} = \sqrt{3}\mathrm{V}_{an}\angle 30^{\mathrm{o}}$), so one has:

$$\mathrm{V}_{LL} = \begin{cases} 115kV\angle 0^{\mathrm{o}} \\ 115kV\angle 120^{\mathrm{o}} \\ 115kV\angle 240^{\mathrm{o}} \end{cases} \rightarrow \mathrm{V}_{LN} = \begin{cases} 66.4\angle -30^{\mathrm{o}} \\ 66.4\angle 90^{\mathrm{o}} \\ 66.4\angle 210^{\mathrm{o}} \end{cases} \tag{23}$$

The relation $\mathbf{V}_m = \left[\mathbf{M}^{-1}\mathbf{V}_{\phi}^{\text{initial}}\right]$ gives the modal components, so by using Symmetrical Components one obtains:

$$\begin{bmatrix} V_m^+ \\ V_m^- \\ V_m^0 \end{bmatrix} = \begin{bmatrix} \text{Voltage } \angle -30^{\mathrm{o}} \\ 0 \\ 0 \end{bmatrix} \tag{24}$$

So, using equation (24), the complete representation for a three phase network in steady state is solved with the positive sequence network as:

$$V_m^+ = Z_m^+ \, I_m^+ \tag{25}$$

C) CHARGES

The charges are represented like single impedances connected to the network, which means; by definition the charge is uncoupled so it does not need to be treated by applying the modal transformation.

FINAL MODEL FOR DIAGNOSE PROCEDURE

Using the line and the source modal transformations, the three phase coupled network is represented like three single uncoupled lines like it is shown in figure 5. By simple analysis one could note that in a steady state condition the three phase coupled system could be fully represented by the positive sequence network, so, by applying the inverse modal transformation to the solution of this network one obtains the solution of the three phase coupled one. In a fault condition the voltages and currents in the nearby node will have values not only for the positive sequence one, so this procedure could give enough information to diagnose the fault condition on the system and the kind of the fault. This is the normal procedure to diagnose and characterize a fault in a power electric system. So, based on the information of the symmetrical components the faults are detected and classified.

In figure 5, the dashed lines of the sources means that for negative and zero sequences the value is zero in steady state operation. In case of unsymmetrical charge; if the asymmetry is due a natural over charge, the voltage-current relationship (denoted as V and I respectively) in phase domain is healthy, so the relay does not process the asymmetry like a fault condition.

By example, in a three phase faults one does not has negative sequence current, nether zero sequence current. For single faults there are equal currents in the sequence networks, etc. Table 1 presents these and other features of the relay input signal when these are processed with symmetrical components.

Kind of Fault	Characteristics of V	Characteristics of I
Three phase	$V(p) \neq 0$, $V(n) = V(0) = 0$	$I(p) \neq 0$, $I(n) = I(0) = 0$
Two phase	$V(p) \neq V(n) \neq 0$, $V(0)=0$	$I(p) = I(n)$, $I(0) = 0$
Two phase-ground	$V(p) \neq V(n) \neq V(0) \neq 0$	$I(p) \neq I(n) \neq I(0)$
Single phase	$V(p) \neq V(n) \neq V(0) \neq 0$	$I(p) = I(n) = I(0)$

Table 1. Features of the relay input signals in symmetrical components.

2.3 Fault electrical features

Under the point of view of the relay, the power electrical system have three stages called; pre-fault condition, fault condition (transient condition) and post-fault condition. In the next paragraphs each one will be briefly described.

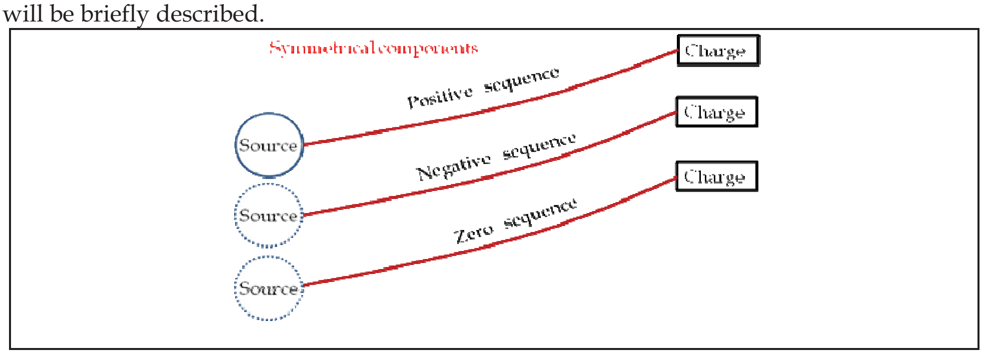


Fig. 5. Model of the three phase line configuration like three single lines.

Pre-fault condition.- Each energy control center takes information from the power electrical network (sub-stations) in real time, so it is possible to know and to supervise the operation limits. The operator engineer takes actions to maintain the steady state condition; that means, frequency, voltage limits, maximum power flows in each line, etc. Under this steady-state condition, the entire power electric system works close to their nominal frequency (60 Hz). This value is achievable by automatic action of the automatic generation control, which creates a balance between generated and consumed active power (Fink *et. al.* 1985), (IEEE Std C37.1 – 1994).

The relation between the voltage phasor and the current phasor is linear, so if the voltage is constant (operative condition) and the current grow up from its minimum value to its maximum depending of the demanding energy, the voltage-current relation each phase is out of the fault characteristic zone, which is defined with the relation resistance-inductance of the line. Figure 6 shows the characteristic zones of relay and the trajectory of a typical fault. This trajectory is out of the fault zones in the steady state operation, and it is maintain out of the fault zones for this operative condition.

Fault condition.- This is a transient condition phenomena because the protection devices acts as fast as possible to disconnect the faulted element. This is the main purpose of a relay and it is also part of the topic of the present work. This stage involves a number of actions beginning with topological changes, automatically produced by action of local protections. The fault clearing requires the use of substation measurements, relay coordination, and communication systems. This stage ends when protections stop disconnecting those elements that were affected by the fault or situated inside the protection zone. Nowadays during a transient state is common the use of load shedding, blocking schemes, and dedicated controls. Most of these schemes can take action in milliseconds, so these schemes become the first automatic corrective action (Madani *et. al.* 2004), (Guzman *et. al.* 2006). After that, like an off line procedure means after the logical decision of the relay (tripping decision), the relay classifies, locate, typifies and disconnect the fault. In a fault condition, the voltage-current relation in not linear because the inclusion of the fault resistance in the path of the energy, so it is beginning a trajectory to the fault zone. The inclusion into the fault zone is not instantaneously because the computation of the phasor is due with a cycle and all the samples but one are healthy. Sample by sample the data window to compute the phasor is fully with fault data, this defines a fault trajectory (L-R-t trajectory). Figure 6 shows the behavior of this trajectory for a typical fault.

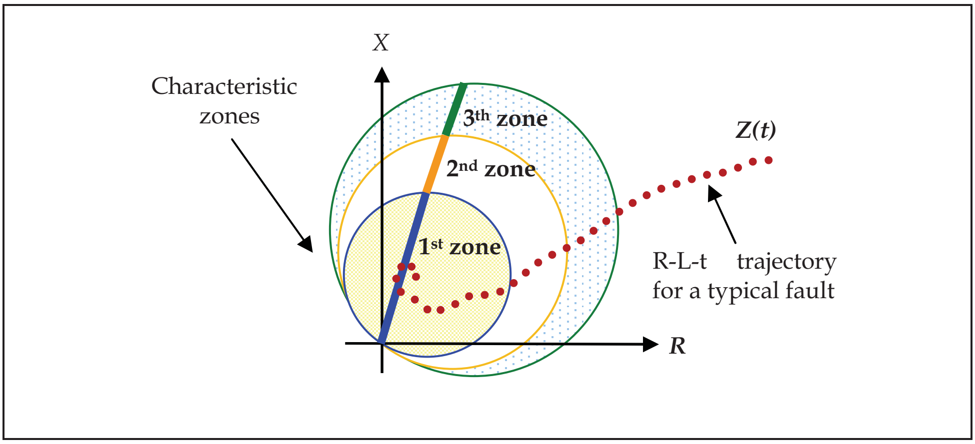


Fig.6. Characteristic zones of a relay

A fault classify algorithm identifies the kind of fault being based in the information of the modal transformation. By example, in a three phase faults one does not has negative sequence current, nether zero sequence current. For single faults there are equal currents in the sequence networks, etc. Note that table 1 presents these and other features of the relay input signal.

Physically, the line could present very complex faults, although protection is develop only to four groups of faults: a) three phase faults, b) two phase faults, c) two phase faults to ground and d) single faults. Figure 7 represents the faults statistical of one year in the Mexican Western Transmission Network. The RELIEVE was consulted to extract the events of the period with a confirmed fault. This system confirms that 69% were single faults, 19% two phase faults and 3% three phase faults.

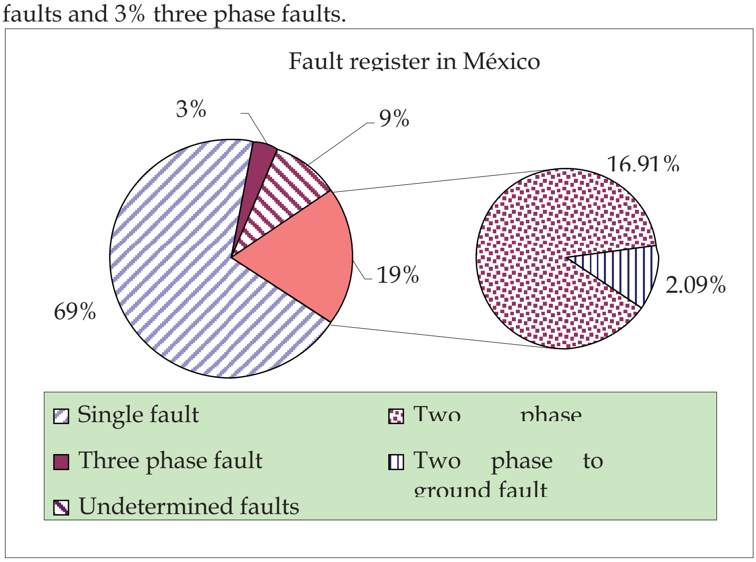


Fig. 7. Percent of faults in the MWTN in 2006

Post-fault condition.- Once the faulted elements are disconnected, the entire network arrives to a different steady state operation condition. The operator engineer takes corrective actions to reach the normal operation condition. Normally, he leads the network to the new steady state without losing more electrical elements, which means, he maintains the network as healthy as possible. This state can remain for several seconds or minutes until to reach another steady state normal condition, in which, there exist a balance between charge and generation.

2.4 Diagnosis Example

For illustrate the diagnoser behavior in power electrical systems consider the power electrical network of the figure 8. In a steady state operation, I^{abc} measurements in each relay don't overpass the adjust pick up. In this specific point of operation the entire network is healthy, that mean, the electrical system is working normally. Figure 8 shows a simple network in a steady state condition, this figure shows how the power flows from generator 1 and 2 to the charge.

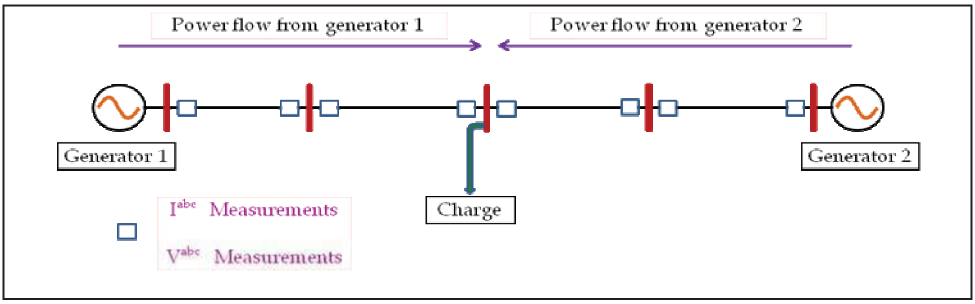


Fig. 8. Steady state operation

While the information of energy control center from the power electrical network (sub-stations) is into the operation limits, the operation of the electrical network is mantanied. When a fault occurs, it is established a trajectory from the generators to the fault point, this is shown in figure 9. In this case, the fault is in the closer line to the generator 2. Analyzing the fault from the point of view of the generator 1, there are four relays that detect the fault in from of them. All relays process the signal as it is shown in figure 2 (figure with the operative times), then each determine is fault zone (figure 6 has the relay circles). Like a resulting of this process, each relay determines its tripping time. The closer relay to the fault detects the fault at the first zone so acts instantaneously, the next in the second one so acts with a delay and the next in the third one so act with an additional delay, the last one (and so on in case of more relay) see the fault out of the protection zone for which they were programmed. There are some relays that detects the fault on behind, so these relays don't act. From generator 2, there is only one relay which determines the fault location at the first zone, so this relay acts instantaneously.

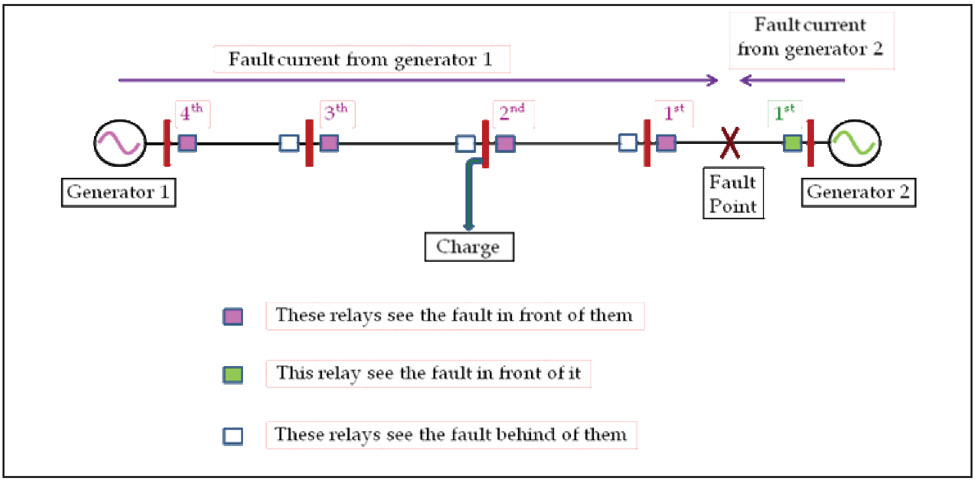


Fig. 9. Fault in the electrical system

Each relay into the protection zone 1, 2, 3 and 4 makes the digital process as illustrated in the figure 9 So, each relay into the protection zone 1 see the fault instantaneously, while that the others relays has a delay. In the case of the protection zone 2 the additional delay is one, into the protection zone 3 the additional delay is two, and in the protection zone 4 is considered as out of operation zone. Then all relays from the figure 1 see the fault, and the power electrical network is in pre-fault state.

The next step is analyzing the voltages and currents signals of the relay into the protection zone 1. These signals are passed through the relay internal transducers, and then the signals are filtered before the analogical-digital conversion. Later a digital filter is used to eliminate the superior harmonics and the no-periodic exponential component still remaining; the useful filters are the finite impulse response ones like the Fourier or cosine types. Remember that to fulfill the window with the fault signal, of one cycle the normal rate of relays is of 32 samples by cycle.

If the fault signal is complete, i.e. it is detected 32 samples in a cycle, and then power electrical network change of the pre-fault to fault state. In other case, when the fault signal is not complete, i.e. it is not detected 32 samples in a cycle, power electrical network change from the pre-fault to normal state.

For this example is considered that the fault signal is complete, then as next step the fault classify algorithm based in the information of the modal transformation identifies the kind of fault. Finally, the electrical components conected to the relay in protection zone 1 are desconnected.

Based on the voltages and currents measurements and its digital processing with a relay to maintain the operation of the power electric system; in the next section we will propos represent with an Interpreted Petri Net the operational behaviour each component for he network in steady state (normal condition), this Interpreted Petri Net will represent the diagnoser. Under the point of view of the relay, the power electrical system have three stages called; pre-fault condition, fault condition (transient condition) and post-fault condition, the Interpreted Petri Net model for the power electrical system includes some transitions that captures these three stages. Also other real condition of the electrical systems is that a fault is detected with a delay of one cycle due to digital filter (32 samples), thus the pre – faulty transition is fired when a faulty condition appear. On the other hand the reset transition fires when is detected that the system operates in normal conditions and it is necessary reset the pre – faulty condition, so the system change from pre- fault state to normal state.

3. Petri nets and Interpreted Petri nets

This section presents a review the main concepts of the Petri net (PN) and Interpreted Petri Net (IPN) formalism used in this chapter. An interested reader can consult (Ramírez-Treviño et al., 2004), (Desel et al., 2005), (Santoyo et al., 2001) and (Ramírez-Treviño et al., 2003) for more details.

3.1 Petri Nets

Definition 1: A PN system is a pair (N, M_0) where $N = (P, T, I, O)$ is a bipartite digraph which specifies the net structure and $M_0 : P \rightarrow Z^+$ is the initial marking. Each element of N is defined as follows $P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places; $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions; $I : P \times T \rightarrow Z^+$ and $O : P \times T \rightarrow Z^+$ are functions representing the weighted arcs going form places to transitions and from transitions to places, respectively. The initial marking of PN M_0 is a function that assigns to each place of N a non-negative number of tokens, depicted as black dots inside the places.

A PN structure N can be represented by its incidence matrix $C = [c_{i,j}]_{n \times m}$, where $c_{i,j} = O(p_i, t_j) - I(p_i, t_j)$. The sets $\bullet t_j = \{ p_i \mid I(p_i, t_j) \neq 0 \}$ and $t_j \bullet = \{ p_i \mid O(p_i, t_j) \neq 0 \}$ are the set of input and output places of a transition t_j respectively, which are denominated predecessors and successors of t_j respectively. Analogously, the sets of input and output transitions of a place p_i are $\bullet p_i = \{ t_j \mid I(p_i, t_j) \neq 0 \}$ and $p_i \bullet = \{ O(p_i, t_j) \neq 0 \}$ respectively. In a PN system, a self-loop is a relation where $c_{i,j} = O(p_i, t_j) - I(p_i, t_j) = 0$ and $O(p_i, t_j) \neq 0$, $I(p_i, t_j) \neq 0$.

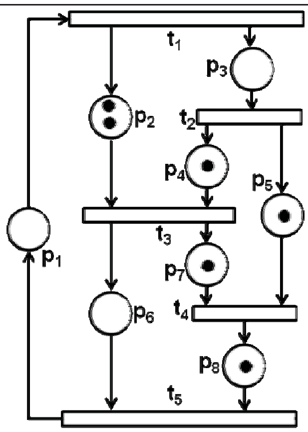
The marking at the *k*-th instant is often represented by a vector $M_k = [M_k(p_1) \quad M_k(p_2) \quad \cdots \quad M_k(p_n)]^T$. Hereafter, a marking M can be represented by a list $M = [1^{M(p_1)}, 2^{M(p_2)}, \cdots, i^{M(p_i)}, \cdots, n^{M(p_n)}]$ where *i*-th item is omitted if $M(p_i) = 0$ and exponents $M(p_i) = 1$ are also omitted. For example, a marking $M = [2 \quad 0 \quad 1 \quad 1]^T$ can be represented by the list $M = [1^2, 3, 4]$.

A transition t_j is enabled at marking M_k if $\forall p_i \in P$, $M_k(p_i) \geq I(p_i, t_j)$; when an enabled transition t_j is fired, then a new marking M_{k+1} is reached. This new marking is computed as $M_{k+1} = M_k + Cv_k$, where v_k is an *m*-entry firing vector whit $v_k(j) = 1$ when t_j is fired once and $v_k(i) = 0$ if $i \neq j$ and t_j is not fired, v_k is called Parikh vector; the equation

$M_{k+1} = M_k + Cv_k$ is called the PN state equation. The *set of enabled transitions* at marking M_k is $E(M_k) = \{t \mid \forall p \in P,\ M_k(p) \geq I(p,t)\}$.

A *firing sequence* of an PN system (N, M_0) is a transition sequence $\sigma = t_i t_j \ldots t_k$ such as $M_0 \xrightarrow{t_i} M_1 \xrightarrow{t_j} \cdots \xrightarrow{t_k} M_k$.. The *firing language* of (N, M_0) is the set $L(N, M_0)$ = $\{\sigma \mid \sigma = t_i t_j \ldots t_k \wedge M_0 \xrightarrow{t_i} M_1 \xrightarrow{t_j} \cdots \xrightarrow{t_k} M_k$, while the Parikh vector $\vec{\sigma}: T \rightarrow (Z^{+})^m$ of σ maps every $t \in T$ to the number of occurrences of t in σ. The fact of reaching M_k from M_0 by firing an enabled sequence σ is denoted by $M_0 \xrightarrow{\sigma} M_k$. The set of all reachable markings from M_0 is $R(N, M_0)$ = $\{ M_k \mid M_0 \xrightarrow{\sigma} M_k$ and $\sigma \in L(N, M_0)\}$ and it is called *reachability set*.

Example 1: Consider the PN of Figure 10.a. The net consists of 8 places $P = \{p_1, p_2, \ldots, p_8\}$ and 5 transitions $T = \{t_1, t_2, \ldots, t_5\}$. The incidence matrix is illustrated in the figure 10.b.



(a)

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

(b)

Fig. 10. a) Petri Net System A, b) Incidence matrix of Petri Net System A.

The sets of input and output places of t_1 are $\bullet t_1 = \{p_1\}$ and $t_1 \bullet = \{p_2, p_3\}$ respectively. The initial marking is $M_0 = [0 \quad 2 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1]^T$ or M_0 = [2^2,4,5,7,8]. The set of enabled transitions at M_0 is $E(M_0) = \{t_3, t_4\}$. When transition t_3 fires the net reaches the marking M_1 = [5,6,7^2,8].■

3.2 Interpreted Petri Nets

This chapter uses Interpreted Petri Nets (IPN), an extension to PN (Meda M. E., et al., 1998). This extension consists in assigning input and output signals to PN models. Formally IPN are defined as follows.

Definition 2: An Interpreted Petri Net (IPN) system is a 6-tuple $Q = (N', \Sigma, \Phi, \lambda, \Psi, \varphi)$ where $N' = (N, M_0)$ is a PN system; $\Sigma = \{\alpha_1, \alpha_2, \ldots, \alpha_r\}$ is the input alphabet, where α_i is an input symbol; $\Phi = \{\delta_1, \delta_2, \ldots, \delta_s\}$ is the output alphabet of the net, where δ_i is an output symbol;

$\lambda : T \to \Sigma \cup \{\varepsilon\}$ is a function that assigns an input symbol to each transition of the net, with the following constraint: $\forall t_j, t_k \in T$, $j \neq k$, if $\forall p_i \quad I(p_i, t_j) = I(p_i, t_k) \neq 0\}$ and both $\lambda(t_j) \neq \varepsilon$, $\lambda(t_k) \neq \varepsilon$, then $\lambda(t_j) \neq \lambda(t_k)$. In this case, ε represents an internal system event. $\Psi : P \to \Phi \cup \{\varepsilon\}$ is a labelling function of places that assigns an output symbol or the null event ε to each place of the net as follows: $\Psi(p_i) = \delta_k$ if p_i represents a output signal, in otherwise $\Psi(p_i) = \varepsilon$. In this case $P_m = \{p_i \mid \Psi(p_i) \neq \varepsilon\}$, $p_i \in P_m$ is called measurable place and $q = \mid P_m \mid$ is the number of measured places. Finally, $\varphi : R(N, M_0) \to (Z^+)^q$ is a function that associates an output vector to every reachable marking of the net as follows: $\varphi(M_k) = M_k \mid_{Pm}$, where $M_k \mid_{Pm}$ is the projection of M_k over P_m i.e. if M_k = $[M_k(p_1) \quad M_k(p_2) \quad \cdots \quad M_k(p_n)]^T$ and P_m = $\{p_i, p_j, \ldots, p_h\}$ then $M_k \mid_{Pm}$ = $[M_k(p_i) \quad M_k(p_j) \quad \cdots \quad M_k(p_h)]^T$:

Notice that function φ is linear and can be represented as a matrix $\varphi = [\varphi_{ij}]_{q \times n}$, where each row $\varphi(k, \bullet)$ of this matrix is an elementary vector where $\varphi(k, i) = 1$ if place p_i is the k-th measured place and otherwise $\varphi(k, i) = 0$ and it is called non- measured.

The transition input alphabet Σ of an IPN can be thought as actuator signals attached to the transitions of the net. Similarly, the output alphabet can be thought as sensor signals attached to places. In this context, it is possible to distinguish between controllable and uncontrollable transitions, and between measured and non-measured places of the net as established in the following definitions.

Definition 3. If $\lambda(t_i) \neq \varepsilon$ then transition t_i is said to be *controlled*, otherwise *uncontrolled*. T_c and T_u are the sets of controlled and uncontrolled transitions, respectively.

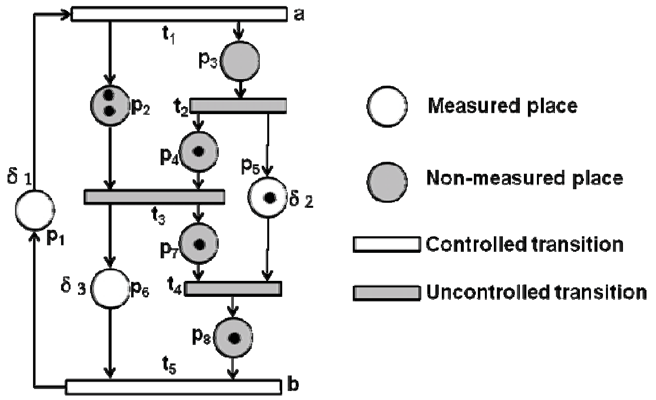
Definition 4. A place $p_i \in P$ is said to be *measured* if the *i*-th column vector of φ is not null, i.e. $\varphi(\bullet, i) \neq 0$; otherwise p_i is *non-measured*. Thus, the set P_m ={ $p \mid \exists j \in 1,2,\ldots,r$ such that $\varphi(\bullet, j) \neq 0$ } is the set of measured places and P_{nm} = $P \setminus P_m$ is the set of non-measured places.

In this chapter, a measured place is depicted as a unfilled circle, while a non-measured place is depicted as a filled circle. Similarly, non-manipulated transitions are depicted by filled bars and manipulated transitions are depicted by unfilled bars. Also, (Q, M_0) will be used instead of $Q = (N', \Sigma, \Phi, \lambda, \Psi, \varphi)$ to emphasize the fact that there is an initial marking in an IPN.

Example 2: Consider the IPN shown in Figure 11a. The input and output alphabets are $\Sigma = \{a, b\}$ and $\Phi = \{\delta_1, \delta_2, \delta_3\}$ respectively. Functions Ψ and λ are given by:

i	1	2	3	4	5	6	7	8
$\Psi(p_i)$	δ_1	ε	ε	ε	δ_2	δ_3	ε	ε

k	1	2	3	4	5
$\lambda(t_k)$	a	ε	ε	ε	b



(a)

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

(b)

Fig. 11. a) Interpreted Petri Net System B, b) Incidence matrix of Interpreted Petri Net System B.

Thus, the controlled transitions are $T_c = \{t_1, t_5\}$ and the uncontrolled ones are $T_u = \{t_2, t_3, t_4\}$. The measured places are $P_m = \{p_1, p_5, p_6\}$ and the non-measured are $P_{nm} = \{p_2, p_3, p_4, p_7, p_8\}$. In this case, the output function is the matrix:

$$\varphi = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{26}$$

The initial output is $y_0 = \varphi(M_0) = [0 \quad 1 \quad 0]^T$. ■

Similarly to a PN, in an IPN system, a transition t_j is enabled at marking M_k if $\forall p_i \in P$, $M_k(p_i) \geq I(p_i, t_j)$; however t_j has fire conditions. When t_j is enabled and t_j is controllable for that t_j fire, it is neccesary that the input signal $\lambda(t_j) \neq \varepsilon$ must be given as input. Otherwise when enabled transition t_j is uncontrollable, then it can be fired. In both cases, when a transition t_j is fired a new marking $M_{k+1} = M_k + C(\bullet, t_j)$ is reached and the output symbol $y_{k+1} = \varphi(M_{k+1})$ is observed.

The following definitions relate the input an output symbol sequences with the firing sequences and the corresponding generated marking sequences. These concepts are useful in the study of the diagnosability property since they are relating to the observed input and output information as the system evolves.

Definition 5. A *firing sequence* of an IPN (Q, M_0) is a transition sequence $\sigma = t_i t_j \ldots t_k \ldots$ such as $M_0 \xrightarrow{t_i} M_1 \xrightarrow{t_j} \cdots \; M_w \xrightarrow{t_k} \cdots$ The *firing language* of (Q, M_0) is the set $L(Q, M_0)$ = $\{\sigma | \sigma = t_i t_j \ldots t_k \wedge \; M_0 \xrightarrow{t_i} M_1 \xrightarrow{t_j} \cdots \; M_w \xrightarrow{t_k} \ldots\}$.

Definition 6. A sequence of *input–output symbols* of an IPN (Q, M_0) is a sequence $w = (\alpha_0, y_0)(\alpha_1, y_1) \cdots (\alpha_k, y_k)$, where $\alpha_i \in \; \sum \cup \{\varepsilon\}$ is the current input of (Q, M_0) when the ouput changes from y_i to y_{i+1}. It is assumed that $\alpha_0 = \varepsilon$, $y_0 = \varphi(M_0)$ and (α_{i+1}, y_{i+1})