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# Resonance in Electrical Power Systems of Petrochemical Plants

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## 1. Introduction

One of the most serious problems in the operation of petrochemical plants is the breakdown of the electrical energy in the production processes. This interruption could be due to the presence of failures that inhibit the continuity and reliability of the electrical energy service. A possible cause of fault in the electrical power system with permanent damages in the primary electrical equipment is the occurrence of the electromagnetic resonance phenomenon. The presence of this phenomenon is directly associated with the grounding scheme of the electrical power equipments. At the moment, in some petrochemical plants only one neutral is connected to ground. When a fault appears, the protection relays operate in order to release the fault and leaving the system temporarily without ground reference. During this time the electrical system remains floated the resonance phenomenon can appear. In petrochemical plants, it is a common practice to have a neutral bus where all the power equipments are connected through an energy cable with a length up to 1 km, with a parasitic capacitance in the order of 50 to 1,000 nF.

This chapter provides an analysis of research on the occurrence of resonance overvoltages in the electrical power system of petrochemical plants. Using digital simulation by *Graphic Alternative Transients Program (ATPDraw)* from *EMTP* was determined that this phenomenon appears when the electrical system does not have reference to ground. It was found that the occurrence frequency of this phenomenon is within a range near to 240 kHz and the magnitude of the overvoltages is in the order of 10 to 20 p.u. Likewise, the evidence of practical cases are discussed where the results were catastrophic for the plants. Also, an analysis of overvoltages by connecting potential transformers windings in open delta is presented.

As a practical solution to keep away from the presence of overvoltages by series resonance, a hybrid neutral grounding scheme is used with the aim of avoiding the power system could be floated during stationary and fault operation of the electrical power system in petrochemical plants. Hybrid neutral grounding consists on an implementation of high resistance grounding in parallel with the low resistance scheme on each of the electrical generators.

The solution for avoid series resonance in potential transformer with open delta windings is the used of wye connection to ground.

## 2. Grounding methods in petrochemical plants

The electromagnetic resonance phenomenon, will be described in section 3, it is directly associated with the method of grounding the electrical system of the petrochemical plants. Protection schemes and practical grounding of industrial power systems of medium voltage, such as industrial petrochemical plants, are based on IEEE standards, the National Electrical Code (NEC), IEC standards and technical publications [IEEE Standard 141-1993; IEEE Standard 142-1982; IEEE Standard 242-1986; IEEE Standard 241-1983; ANSI C62.92-1987; National Electrical Code National; IEC 61936-1 2002; IEC 60364-1 2001; Dunki-Jacobs, 1977].

The grounding of the electrical system is physically connecting a point of the system (usually the neutral transformer or generator) to ground and create a reference voltage for the electrical system [IEEE Standard 141-1993; IEEE Standard 142-1982; IEEE Standard 242-1986; IEEE Standard 241-1983; ANSI C62.92-1987; National Electrical Code National; IEC 61936-1 2002; IEC 60364-1 2001; Dunki-Jacobs, 1977].

In practice, the electrical power system of a petrochemical plant on 13.8 kV is grounded using "low resistance" method, grounding only one or maximum two points of the system, as the neutral of star winding neutral transformer or generator. Also, on 4.16 kV transformers are used in delta-star connection so the neutral is grounded using the "low resistance" method. At the level of 480 V as used by the method of "solid" grounding by the neutrals transformers.

On the other hand, when a fault to ground occurs on 13.8 kV, the system can be "floating" as described in section 2.3, in this case, the system is "ungrounded". The following describes each of the grounding methods used in the electrical system of the petrochemical pants.
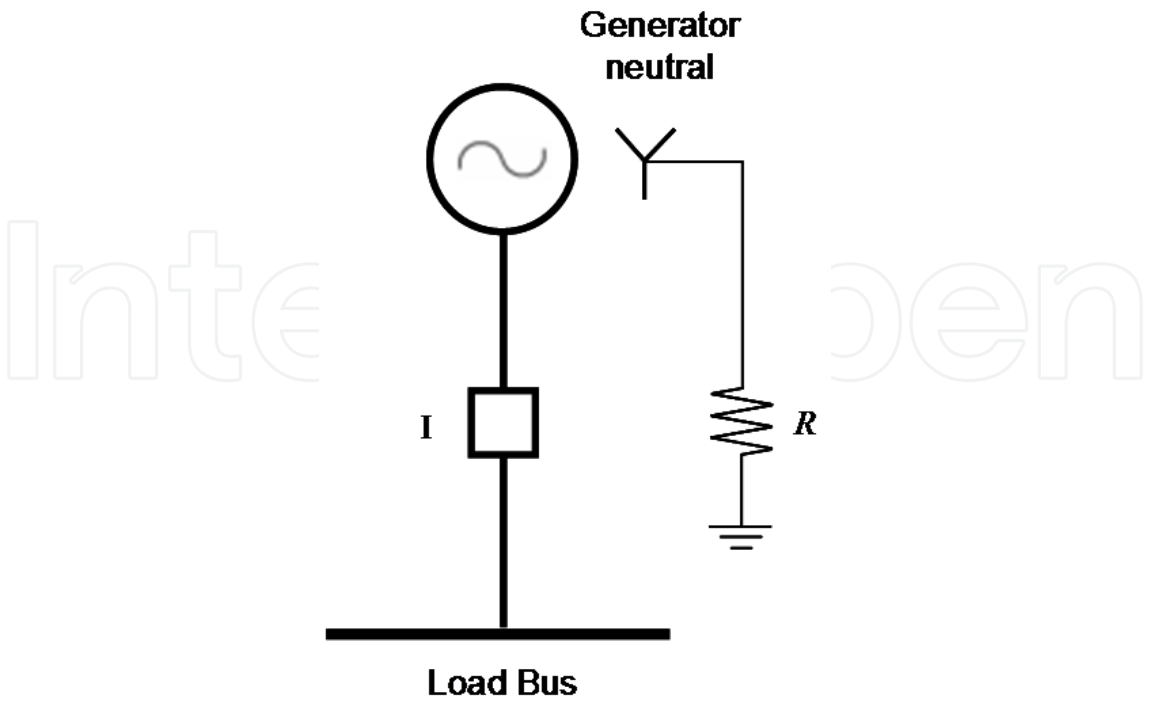


Fig. 2.1.1. Resistance with grounding.

## 2.1 Low resistance grounding

In large systems where we have a high capital investment in equipment or losses which have a significant economic impact, we use the low impedance grounding [Manning, 1964; Shipp & Angelini, 1991]. In this scheme, a resistor is connected, normally a value that allows only a ground fault current of 200 to 800 A, through the neutral grounding system, see Fig. 2.1.1. As the grounding impedance is a resistance, any transient overvoltage is quickly damped and the overvoltage does not stay for a long time [Shipp & Angelini, 1991].

## 2.2 Solidly grounding

Solidly grounding systems are the most commonly used. These schemes can be used in systems operating with a single phase loads, tending to a safe operation, see Fig. 2.2.1. If the system is not solidly grounded, the neutral system remains floating to ground, and remains as function of the load line to neutral and exposed to unbalanced voltages and instability [Shipp & Angelini, 1991].
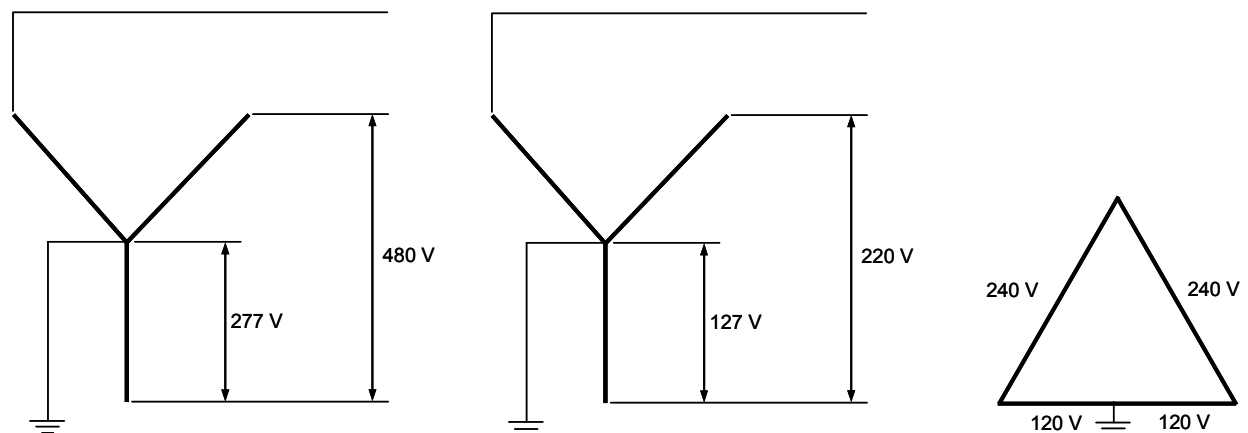


Fig. 2.2.1. Neutral solidly grounding.

## 2.3 Isolated from ground

A floating system is used in those systems where service continuity is the main concern, see Fig. 2.3.1. The perception is that the floating systems provide greater continuity on the service. This is based on an argument that the ground fault current is smaller and therefore, the heating produced by the presence of such failure is negligible [Shipp & Angelini, 1991]. That way, the line to ground faults can remain on the system until it's convenient to remove them. This idea has some validity only if snapshots or "solids" failures are considered. However, in practice, most faults begin as ground faults by arcs of low energy. When starting a ground fault arc, we can have the following problems:

- Multiple ground faults
- Resonance
- Transient overvoltages

Multiple failures to ground may occur in floating systems. While a ground fault on an isolated system does not cause an exit, if the fault continues, increases the possibility of occurrence of a second fault in another phase. That is because the ground insulation of the

unfaulted phases acquires the phase to phase voltage. In other words, the insulation is subjected to stress 73% above the normal operating condition.
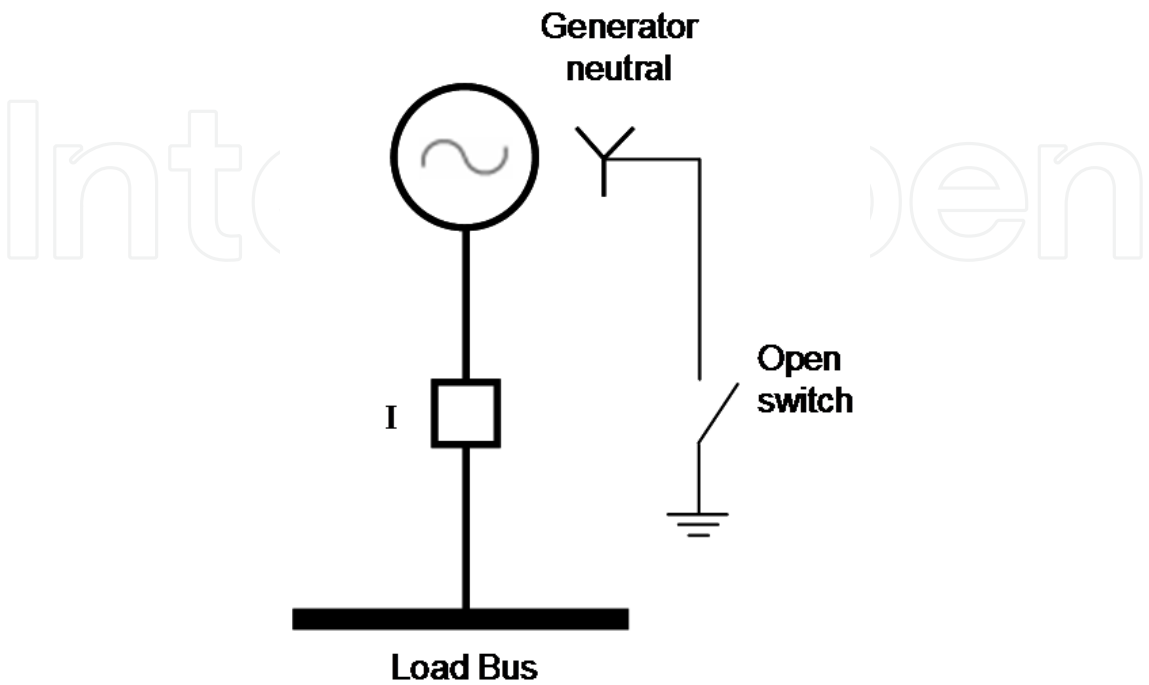


Fig. 2.3.1. Ungrounded neutral.

Even though it isn't common, the phenomenon of resonance can occur when one phase is grounded through an inductance, for example, a ground between the winding of the instrument transformer. When this happens, the high current flow causes high voltages across the unfaulted phases. Transient events due to switching or intermittent faults to the ground can produce overvoltages on floating systems [Shipp & Angelini, 1991].

### 2.4 Advantages and disadvantages of grounding methods

Table 1. summarizes the most relevant characteristics of grounding schemes, available in the petrochemical plant electric system [Shipp & Angelini, 1991; Reyes Martínez, 2001].

## 3. Series resonance

Series resonance is the tuning of the inductive and capacitive reactance of the elements of an RLC series circuit. During the occurrence of this phenomenon dangerous overvoltages may occur depending on quality factor Q of the circuit [Rüdenberg, 1950; Boylestad, 1998; Boylestad, 1998; Fuentes Rosado, 1988], that way damage to associated equipment. This effect is observed in the digital simulation results presented in section 3.3. The resonance can also occur by the presence of harmonic frequencies [Lemerande, 1998; Currence, et al., 1995; Girgis, et al., 1993; Fujita, 2000]. This sections contains a description of the resonance phenomenon, the causes may brings as present in the electrical system of an industrial petrochemical plant during a fault.

|  | floating (ungrounding) | Solidly grounding | Low resistance grounding |
|---|---|---|---|
| Single phase fault current in percent of the three phase fault current | ≤ 1% | Variable, can be 100 % or greater | 5 a 20% |
| Transient overvoltage | ≤ 6 p.u. | ≤ 1.2 p.u. | < 2.5 p.u. |
| Segregation automatic fault zone | No | Yes | Yes |
| Surge arresters | Floating neutral type | Grounding neutral type | Floating neutral type |
| Comments | Not recommended due to the overvoltages and the impossibility of segregation of the fault | Typically used in systems of 600 V or less and up to 15 kV | Generally used in industrial systems from 2.4 to 15 kV |

Table 1. Characteristics of the electrical system with several grounding methods currently used in petrochemical plants.

## 3.1 Description of grounding practices that induce the presence of this problem

It is extremely necessary to maintain the electrical power supply of petrochemical power plants; therefore most of them have their own electrical energy generation. In some petrochemical plants there is a common practice to associate an electrical generator with a load connected directly to the electrical generator terminals. Most of the plants use 30 MW generators at 13.8 kV with a load on the order of 15 to 20 MW associated to their terminals. The generators are interconnected trough a synchronizing bus with short circuit current limiting reactors as shown in Fig. 3.1.1. The use of these limiting reactors is associated with voltage regulation problems and with the necessity to overexcite the generators, causing problems with generator stator core. However, the use of this scheme maintains the continuity of energy supply to the load sustained through the public network when generators are out of service.
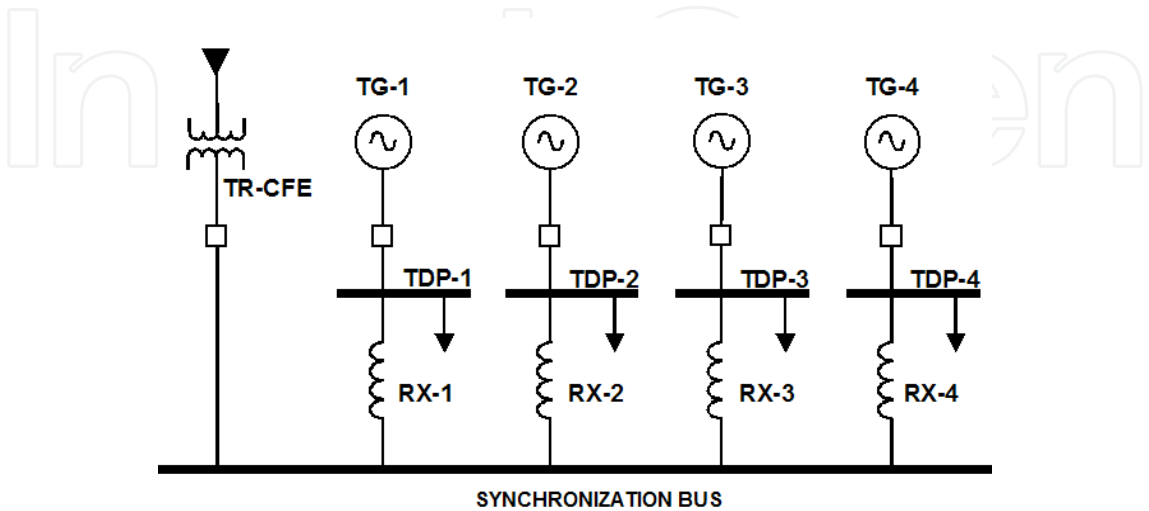


Fig. 3.1.1. Typical generation scheme of a petrochemical plant.

### 3.2 Factors affecting series resonance

Petrochemical plants with 13.8 kV generators; use low-resistance neutral grounding method at just one generator. The ground connection through a resistance bank has a value of 8 to 13.2 Ω which limits the ground fault current between 600 and 1,000 A. In other hand, if all generators are connected to ground, all protection devices will operate to leave the entire generators out of service. Furthermore, the short circuit ground fault current increases at a point that it will easily exceed the 1,000 A.

The neutral grounding method used in a petrochemical plant is shown in Fig. 3.2.1. The system has two power units, the first unit consists in two generators of 32 MVA (TG-1 and TG-2) and the second one with 2 generators of 40 MVA (TG-3 and TG-4). The four neutral generators are connected to a neutral bus through an interrupter. The neutral bus has a low resistance bank connected to ground. Therefore, only one generator is connected to ground.

When a ground fault occurs in a cable or in any other electric power equipment and this does not release appropriate, the protection system acts over the generator with the neutral connected to ground. The generator outs of service and the system operate temporality "ungrounded". Even though, it is in fact connected to ground through the ground system capacitance.

### 3.3 Overvoltages caused by series resonance

Considering an ungrounded generator, that feeds an electrical load, as shown in Fig. 3.3.1. The generator model is represented by a source and an inductance in series. The cable and the load inductance are illustrated too. Also it represents the cables capacitance, the capacitors banks and the surge arresters.
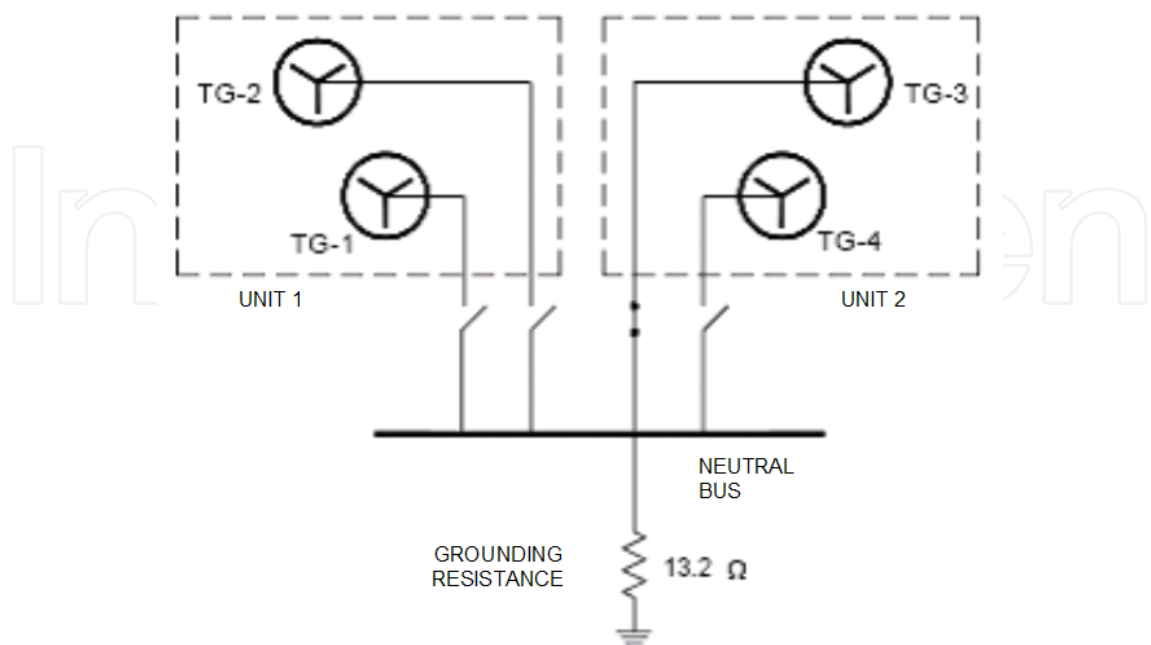


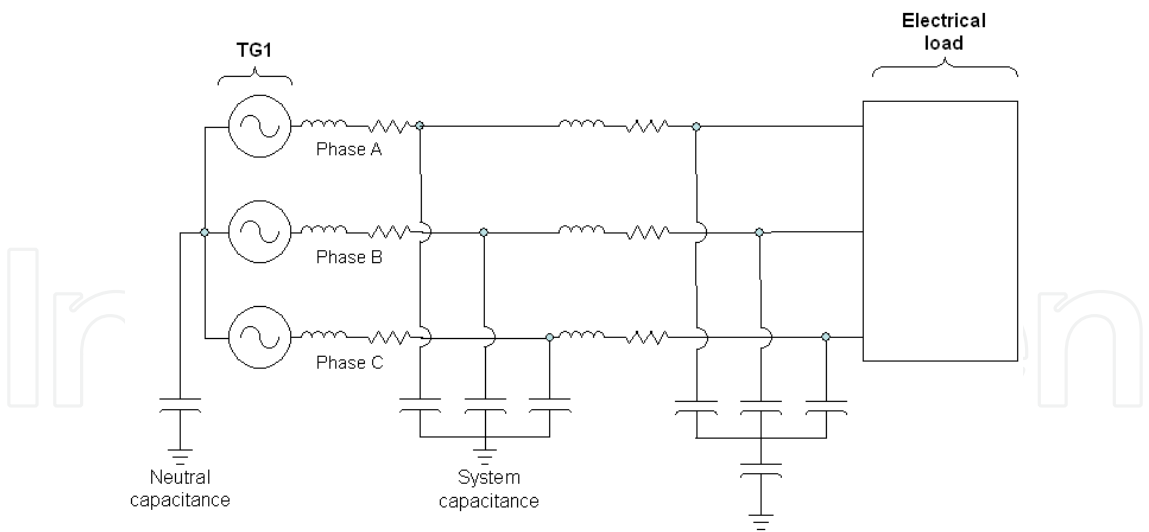Fig. 3.2.1. Actual generator neutral grounding scheme.

Fig. 3.3.1. Diagram of one generator neutral grounding.

The system has a steady performance. The load is feeding by the generator; the neutral current is almost zero. The generator is grounded by its own capacitance. There is not current through the neutral generator and there is a third harmonic voltage of 1 kV peak to peak approximated. When a ground fault occurs in the system, a return current through the generator capacitance and a voltage appears through the neutral, which affects the voltage applied in the un-faulted phases, as shown in Fig. 3.3.2.
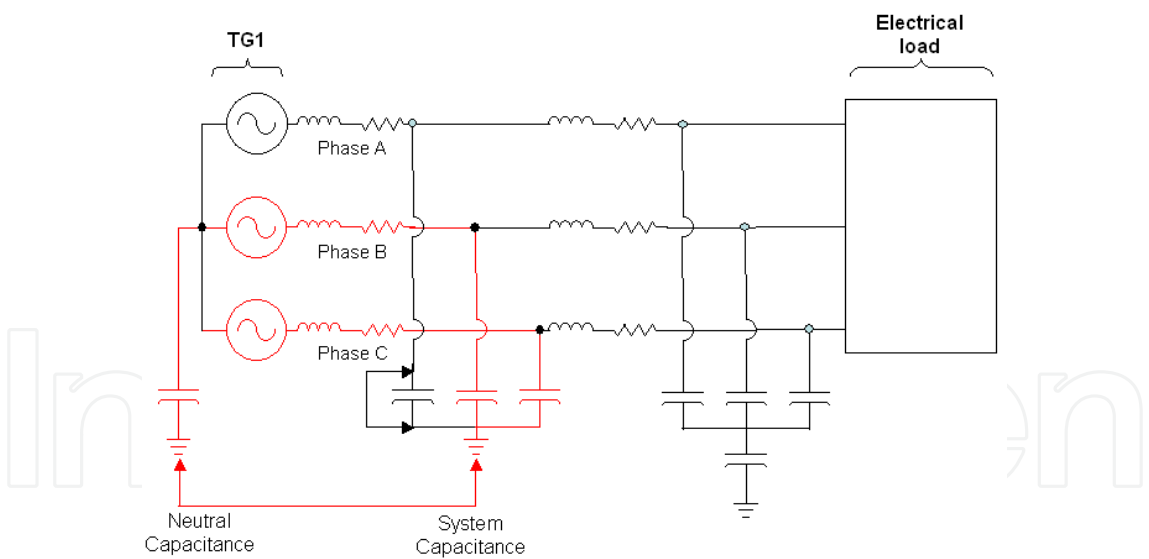


Fig. 3.3.2. Fault in phase A and current return path.

When a current is injected through the neutral capacitance, the neutral potential increases, in such a way that ground potential of the phases change to voltage between phases due to neutral shift. Although it is negative, this situation is considered in the electrical systems designs. For example, power cables are designed with 173% of insulated level. As shown in Fig. 3.3.3, an increase in the magnitude for the next phase in sequence to the ground fault phase is observed.

This voltage increase is not a problem for electrical equipments due to it is considered in design. The problem turns pessimistic due to short circuit current of ground fault phase to neutral, affecting the waveform of un-faulted phases, which stay with a no sinusoidal waveform. As a result of the interaction between fault phase and the others phases, it is obtained a waveform, as shown in Fig. 3.3.4**.**
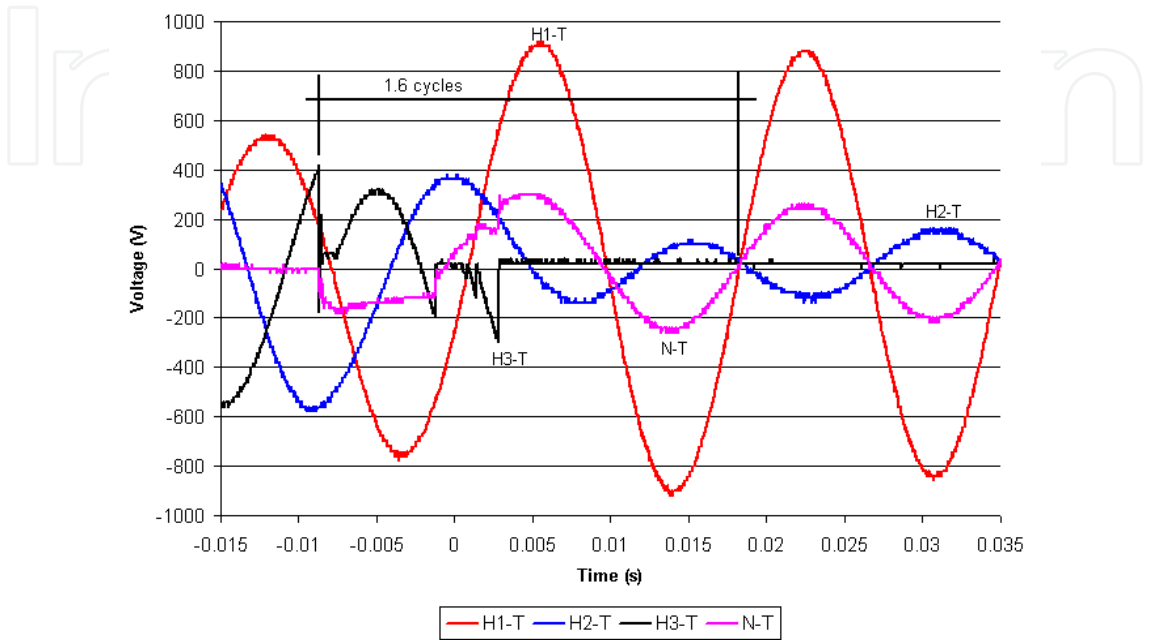


Fig. 3.3.3. Voltage increase in the no fault phase A into an ungrounded circuit.

During a short circuit the phase-neutral voltage is affected, and it is attributable to harmonics components, whose frequency depends on the generator inductance and capacitance equivalent values, furthermore, the equipments and accessories that are connected with the generator to a distribution switchboard. If a Fourier transform is applied to the voltage waveform illustrated in Fig. 3.3.4, it is possible to find the frequency of harmonic components. Fig. 3.3.5 exposes the Fourier analysis of generator phase-neutral voltage.
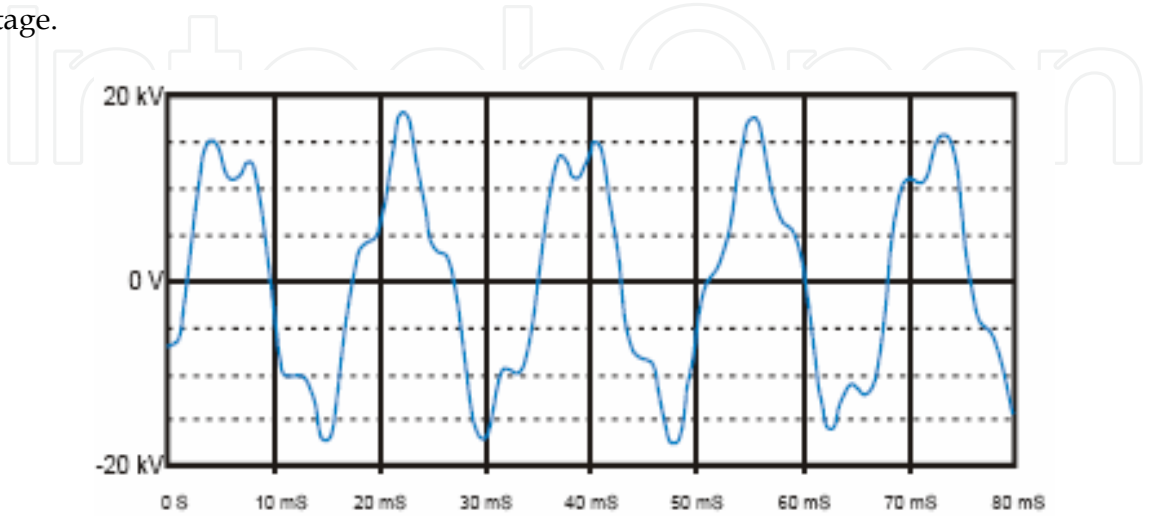


Fig. 3.3.4. Waveform of phase neutral voltage generated during a short circuit.
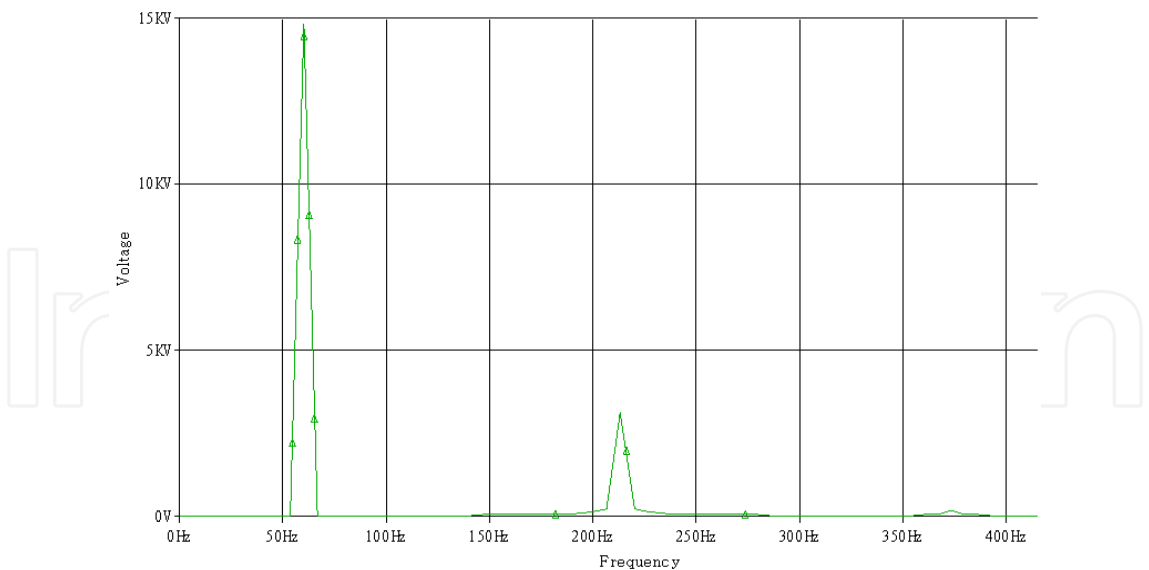
Fig. 3.3.5. Frequency spectrum of the voltage waveform illustrated in Fig 3.3.4.

During the ground fault short circuit, the un-faulted phases have a distorted waveform. With this distorted wave, the generator supplies the demanded electrical energy in conjunction with the electrical public network. At this moment, the question is if all network with capacitance and inductance distributed values of all component, are in resonance or it is represented in somewhere of the circuit where it has appropriate tuned values. Founded evidences in some faults, demonstrate that resonance is located specifically and the damage takes place in the nearby equipments to the overvoltage site. The ground fault occurs in a different phase from that had failed previously. In practice, the second fault could occur at a different site where it occurred at the first time, the crucial condition is that the inductance and capacitance are synchronized and forming a series resonant circuit as shown in Fig. 3.3.2.

## 3.4 Detailed analysis of equations of series resonance

The series resonance phenomenon can occur when a disturbance occurs as a phase to ground fault in power system operation. Resonance occurs when the inductive reactance equals the capacitive reactance [Rüdenberg, 1950; Enríquez Harper, 1978; Boylestad, 1998; Fuentes Rosado, 1988; Halladay and Shih, 1985; Hayt & Kemmerly, 1990; Strum & Ward, 1973; Bodger & Norriss, 1988; Kraft & Heydt, 1984].

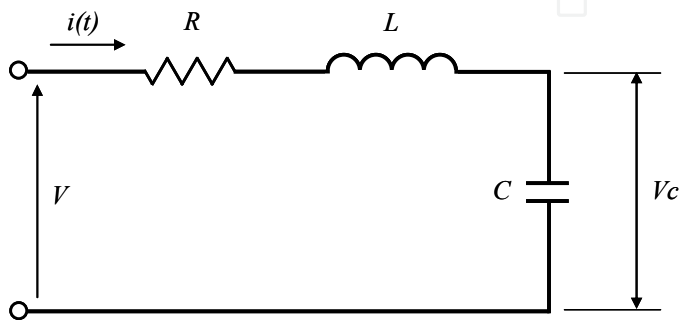In a series *RLC* circuit as shown in Fig. 3.4.1, the current *i(t)* is given by equation (1).



Fig. 3.4.1. Series RLC circuit.

$$i(t) = \frac{v(t)}{\mathbf{Z}} \qquad (1)$$

Where $Z$ is the impedance of the circuit by Kirchhoff's voltage law is equation (2).

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad (2)$$

Where $\omega$ is the angular frequency of the circuit and its value is $\omega = 2\pi f$; the magnitude of $Z$ is given by equation (3).

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \qquad (3)$$

When $X_L = X_C$ or $\omega L = \frac{1}{\omega C}$, the circuit parameters are limited mainly by the resistance $R$ and it says that the circuit is in resonance. Under these conditions the resonance frequency is given by

$$f = \frac{1}{2\pi \sqrt{L\,C}} \qquad (4)$$

For the particular value of the frequency of equation 4, the current $I$ and the voltage $V$ are in phase (P.F = 1.0) and current-voltage relationship agree with Ohm's law. Analyzing the resonant circuit in Fig. 11 is obtaining resonance overvoltage.

$$Vc = \frac{-jX_C V}{R + j\left(X_L - X_C\right)} \qquad (5)$$

in resonance $X_L = X_C$ and

$$V_C = -j\frac{X_C}{R}V \qquad (6)$$

or also

$$|V_C| = Q\,V \qquad (7)$$

Where

$$Q = \frac{\omega L}{R} = \frac{1}{\omega RC} \qquad (8)$$

The parameter $Q$ is the quality factor of the resonant circuit and is defined as $2\pi$ times the storage energy ratio between the energy dissipated in half cycle [Rüdenberg, 1950; Boylestad, 1998; Hayt & Kemmerly, 1990; Strum & Ward 1973].

At resonance, the energy is stored in the inductor and the capacitor and only dissipated in the resistor. Also, the current through the resonant circuit is in phase with the voltage $V$ of power source.

### 3.5 Practical example (showing photos of catastrophic effects in electrical equipment)

In some plants have occurred serious problems related to actual generator neutral grounding. This section describes three events in petrochemical plants.

### 3.5.1 Fault description in Plant "A"

The fault began with ground fault in the TDP-2 – RX-2 feeder (cable), see Fig. 3.5.1.1, when the ground fault occurred in this feeder, the negative sequence current circulated through the TG-3 neutral and TR-CFE transformer, condition that triggered the generator ground protection. After the trip from TG-3 also triggered transformer protection, therefore the power electrical system was temporarily ungrounded. Subsequently, TG-2 differential protection was operated. This protection operated because there was a ground fault in a coil of *R* phase into the TG-2 generator. Based on the system conditions at the time of TG-2 fault occurred, and the position of poles damaged, it is considered that this fault was caused, by the series resonance phenomena as a result of ungrounded system.

The resonance phenomenon occurs at the tuned frequency with the capacitive and inductive reactance of the circuit. In case of industrial system could be defined by 1) system capacitance, it is includes the cable, the windings and parasitic capacitance; and 2) the inductive reactance of the cable and equipment windings.

The generator core damage by electro-erosion, produce by arc flash, is shown in Fig. 3.5.1.2. The arc flash must begin by a magnitude voltage that broke the dielectric distance. For that distance, it is estimated an overvoltage that exceeding 100 kV.
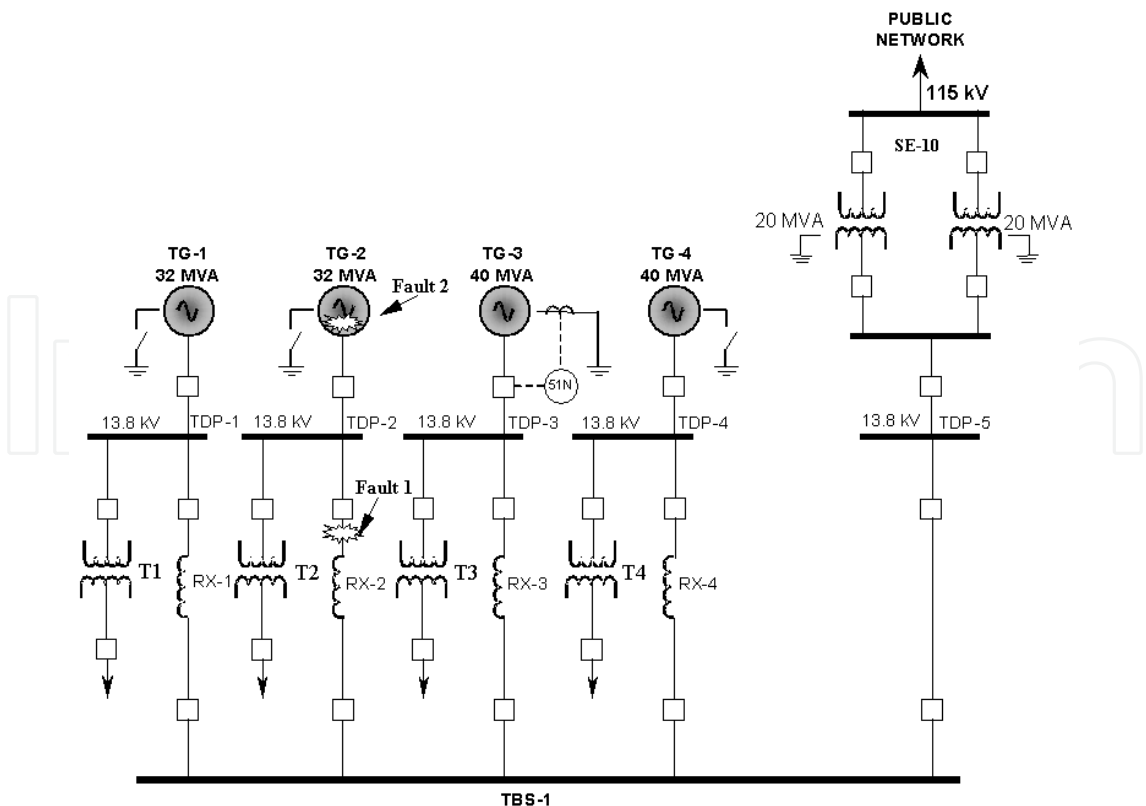


Fig. 3.5.1.1. Localization of faulted cable in the power electrical system.
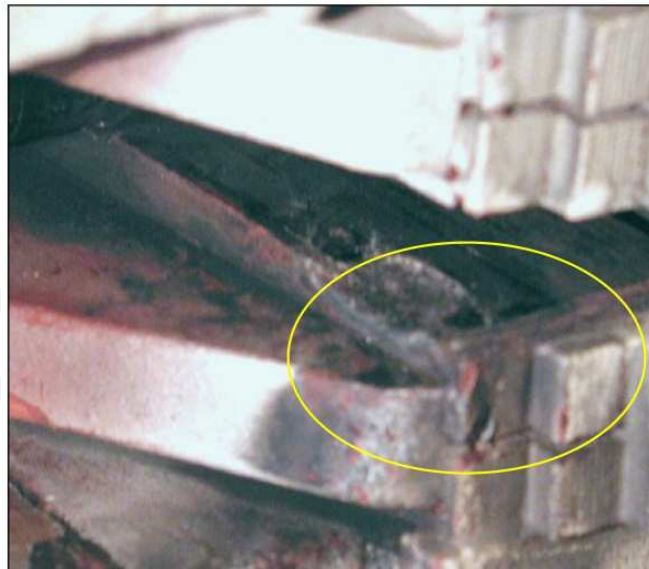
Fig. 3.5.1.2. Damages evidences in the stator core laminations of TG-2.

### 3.5.2 Fault description in Plant "B"

This plant was operated with three electrical generators: TG-2, TG-3 y TG-4. The power electrical system was synchronized to the public network through a "link" principal transformer. The electric network of this plant was ungrounded during a fault or there was not ground reference in system by a previous fault. Subsequently, in another site a fault occurs in a switchboard called "extension bus bar of TG-2" at voltage level of a 13.8 kV. The fault consists of an arc flash between bus bar and switchboard walls when the network was steady. Transient oscillations of the frequencies derived of the arc were tuned to the circuit, and it was in resonance. The evidence shows that intermittent arc flash occurs, promoted electro-erosion as is shown in Fig. 3.5.2.1.

The distance between bus bars and switchboard walls connected to ground was 14 cm; therefore, it must be at least an overvoltage of 160 kV to break down the air dielectric strength. Then, another arc flash occurred in the un-faulted phases, after it there was produced a three-phase fault at bottom of the bus bar. Due to three-phase fault the copper material was fused in bars until it was detected by the network protections.

Another switchboard fault was presented in this plant. The evidence showed that there was an arc flash between CT´s connection bars to the switchboard wall. A few minutes before the fault occurred in the 115 kV transmission line in the public network which was feeding the load plant, then it was produced an overvoltage in the 13.8 kV network of the plant. Due to the principal transformer is connected through a reactor to the synchronizing bus; the transient was spread to the feeder circuits connected to the bus. Due to the disturber in the 115 kV line service, the interrupter was operated. Immediately after, the load segregation system was operated.

The voltage regulator of the TG-4 generator tried to absorb the load, however, the generator left of operation by overexcitation protection. The TG-1 and TG-2 generators continued operating and feeding the not segregated load. Fig. 3.5.2.2 shows the evidence of arc flash between CT´s connection bars and the switchboard wall.

Fig. 3.5.2.1. Electroerosion damages by repetitive or intermittent ground fault arc flash.



Fig. 3.5.2.2. Arc flash evidences between CT's and metallic walls.

### 3.5.3 Fault description in Plant "C"

In the cases above mentioned there was not an evidence of previous fault. In this case, the first fault occurred in a 13.8 kV cable feeder connected to TDP-1 switchboard about 200 meters away from where, 15 seconds after, occurred the second one. The second fault occurs in the called "cell fundamentals" where de protection and measure device's are located. The evidence shows that the generator surge protection capacitors were severely damaged, the connection bars were fused and the two potential open delta connecting

transformers, showed on theirs surfaces, a evidence of three-phase short circuit (see Fig. 3.5.3.1).
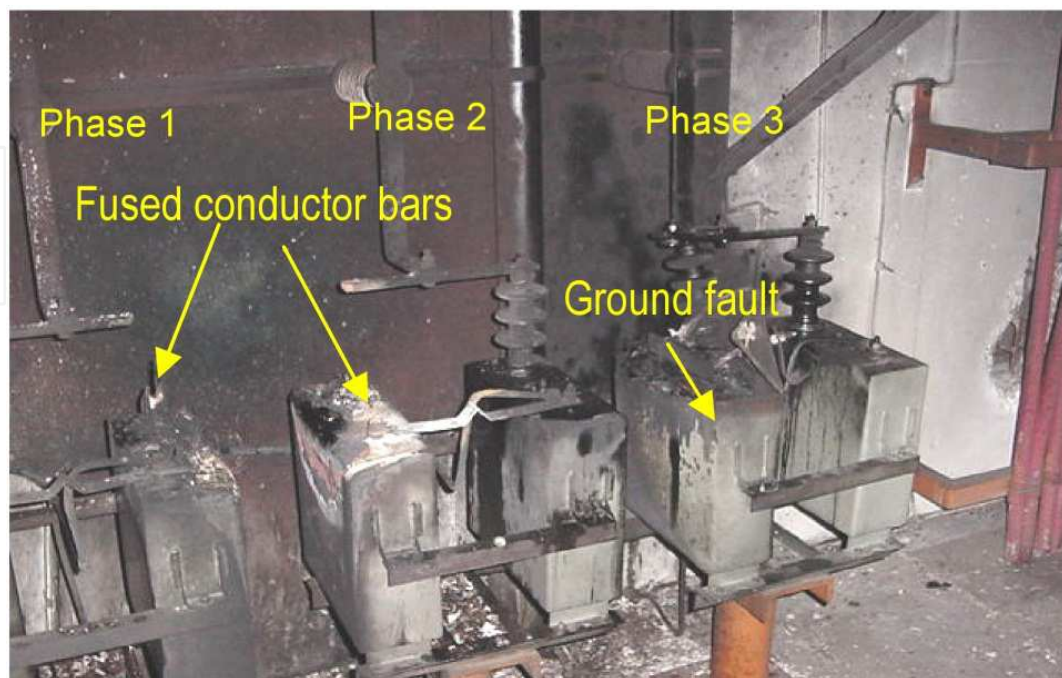


Fig. 3.5.3.1. Capacitor and capacitor bars connections damages.

The fault began in a phase 2 feeder as a ground fault, it had produced an overvoltage in phase 3 with sufficient magnitude to cause the capacitor ground fault. The ground reference during the fault was in TG-3 generator; the current must be circulated through the ground resistance in TG-3. The fault performance was apparently like there was not a ground reference; the zero sequence current did not found ground return, it produced overvoltage in the not fault phases. This fact caused the generator operated like an ungrounded system.

## 3.6 Problem solution

It has been observed trough the years, that in some instances, when there is a ground fault in the 13.8 kV system, the generator that has a reference to ground sees the failure and the protection system takes it out of service. In this conditions, the electrical power system remains without a ground reference without being able to release the failure. The short circuit currents is limited by the capacitance of the generator, that is in the order of 0.5 A. The injected failure current trough the neutral produces a non sinusoidal voltage in the generator output. This voltage excites the failed system and a series resonant circuit can be excited. In this conditions a very dangerous overvoltages are generated. It practice, it has been observed arc flashover between electrodes that are 15 cm apart; and then the overvoltages are estimated in the order of 10 to 12 p.u. So, in order to avoid resonance overvoltages is necessary to have grounded systems to keep and intentional reference to ground. Fig. 3.6.1 shows a high resistance grounded system. When a ground fault occurs the short circuit magnitude is given by the high resistance value, in this diagram is 5 A. Simulations showed there are not maximums overvoltages more than 1.73 p.u. Finally, Fig. 3.6.2 shows a high resistance transformer installed in a petrochemical plant.
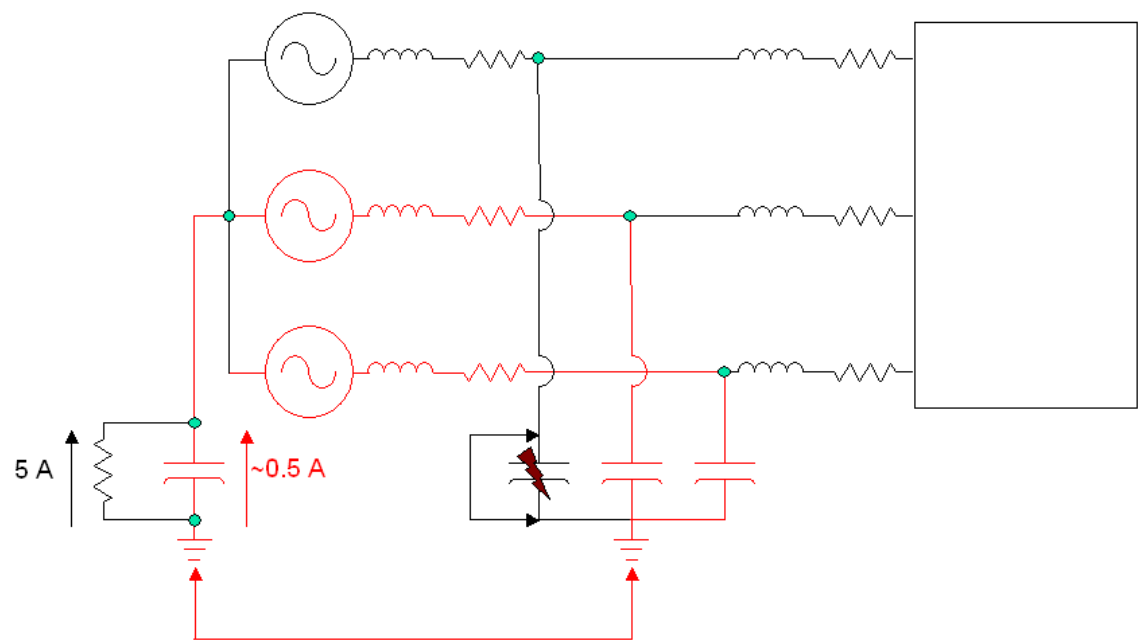
Fig. 3.6.1. High resistance grounded scheme to avoid resonance overvoltages.



Fig. 3.6.2. High resistance transformer installed in a petrochemical plant.

## 4. Resonance in potential transformers

It has been observed that the series resonance can occur in potential transformers (PT). In this case overvoltages were also presented by the series resonance phenomenon.

### 4.1 Description potential transformers in electrical switchgears

The PT is the transformer designed to provide the proper voltage to the measuring instruments such as voltmeters, frequency meters, wattmeters, watt-hour meters, etc., as well as protective devices such as relays, in which the secondary voltage is proportional to the primary and phase shift with respect to it an angle close to zero.

The terminals of the primary winding of a potential transformer are connected to the two lines of the system where is necessary to measure the high voltage and measuring instruments are connected in parallel to the secondary terminals. Its function is to provide an image proportional in magnitude with the same angle of tension in the power circuit connected. There are 2 types of PT´s, one inductive (PT) and a capacitive type (PD).

A common practice in electrical energy distribution switchgears is the open delta connection of PT's used for measurement and protection. However, it is shown that failures occur between phases with relative ease [Magallanes Ramírez & Alba Medina, 1991]. In three-phase industrial systems, the use of this connection involves using only two PT's, so that economically there is a saving in purchasing one PT for each panel. It also requires less space to accommodate two PT's within the switchgears.

The statistics regarding the incidence of failures in PT's, in some industrial plants indicate that as time passes, the number of failures in these devices increases substantially. For example, Fig. 4.1.1 shows the annual failure rate recorded in industrial plants until March 2001.

As shown in Fig. 4.1.1, the failure rate will increase. This is due to growth, sometimes excessive, of the installed capacity carried out without updating studies of the fault current levels and margins of safety switches and feeders. Also it is not considered necessary to make modifications to the grounding system. On the other hand, is a common practice in 13.8 kV to ground only one power equipment, either a generator or a transformer, so that the electrical system is exposed to surges by close-open events on switches, etc., which can be very large.

According to the records that have in some petrochemical plants, PT's that have failed, are usually located near a power source (generator or transformer), which is isolated from ground.

Therefore, considering all the above factors, it is feasible to consider the submission of PT's failures by phenomena of resonance.
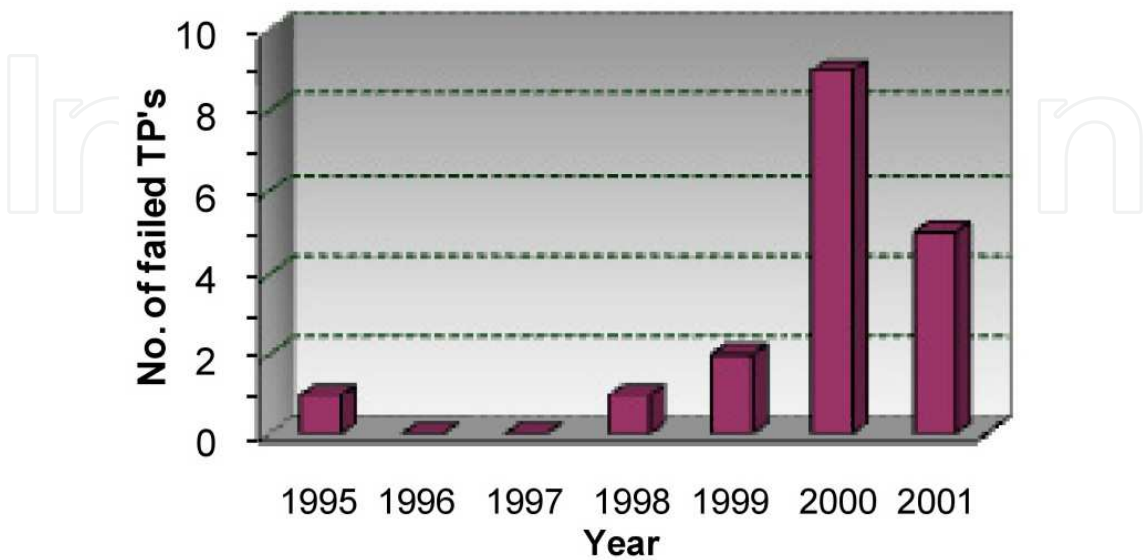
Fig. 4.1.1. Annual rate of PT's failures in petrochemical industrial plants.

**4.2 Description of grounding practices that induce the presence of this problem**

It is estimated that the possible cause of failure of the PT's, is due to series resonance effect caused by the open delta connection of the primary winding of the PT.

The Fig. 4.2.1 shows that when a ground fault occurs, at the end of one of the feeders there is an RLC circuit formed by the resistor (R11 and R12), inductance (L11 and L12) and capacitance (C12) of the feeders. Under fault conditions the current flows through these elements, this stream may contain a component of a frequency (1 to 10 kHz) that could generate a series resonant circuit.

The typical primary winding inductance of a PT is into the order of 28.5 H at 60 Hz, if the power cable would have a length of 1 m, this would present a capacitance of 1 nF. Therefore, in order to present the series resonance phenomenon requires a 990.8 Hz frequency. On the other hand, in the industrial petrochemical plants surges were detected in 5 to 7 kHz. These surges may be caused by maneuvers or system failure, see Fig. 4.2.2. Therefore, it is concluded that the open delta connection of PT's makes possible the resonance effect.
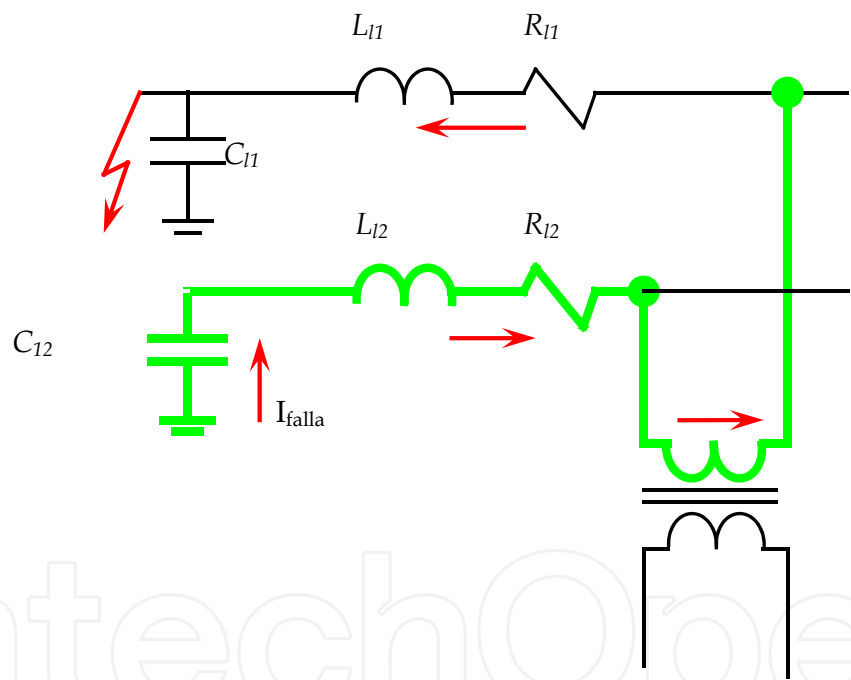


Fig. 4.2.1. Diagram of a PT in open delta connection.

**4.3 Practical example (showing photos of catastrophic effects in electrical equipment)**

Consider the following case, there was a failure of one of the PT's installed on the 13.8 kV level. The PT was located into a medium voltage switchgear connected to the output of a generator in an industrial petrochemical plant in Mexico. PT failure completely destroyed the switchgear that contained the PT, causing in turn the shot of the generators connected to the system and total loss of electrical power plant. As a result, the industrial petrochemical plant was out of operation for several hours, causing significant economic losses. Fig. 4.3.1 shows the damage to the PT, and Fig. 4.3.2, the damage on the switchgear.
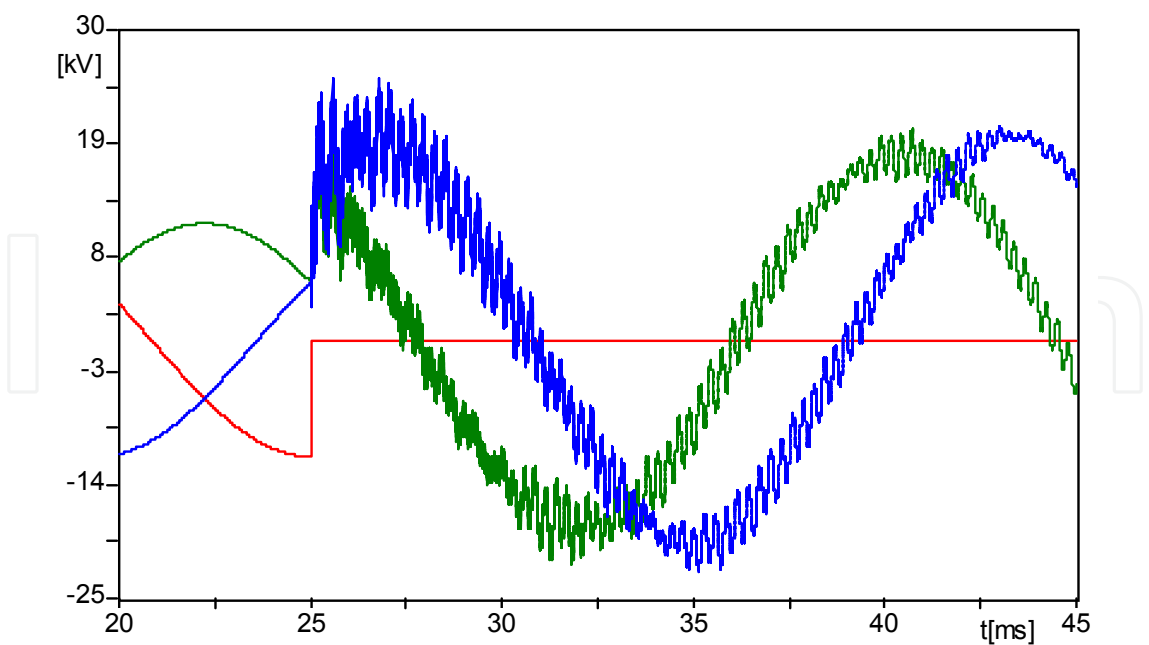
Fig. 4.2.2. Overvoltages registered in an industrial system due to maneuvers in the system itself.



Fig. 4.3.1. Damage to the PT and panel where PT was connected.

Fig. 4.3.2. Damage to the switchgear where the TP was connected.

The switchgear where PT was connected was of kind of metal-enclosed and was composed of 11 panels of 13.8 kV with a current capacity of 2,000 A. Nine of the panels were vacuum switches with their auxiliary equipment. One of the panels was used exclusively for measurement. The remaining panels, was empty because it could not be restored after the failure of one of the PT's occurred three years ago. One of the feeders of the switchgear was connected to one of the generators of the plant.

### 4.3.1 The process of deterioration that causes the failure of PT is slow

The industrial petrochemical plant where the TP failure occurred has a monitoring and recording system for events and variables. Fig. 4.3.1.1 shows the data of voltage, current and power recorded 20 minutes before the failure occurred.

The system logs indicate that the failure of PT began 5'30" before the three-phase fault occurred on the switchgear, see Fig. 4.3.1.2.

According to the records of power, there is an increase of active power on the order of 25% between 3:52:30 and 3:58.00. The PT had a two sections winding, each of 55 layers. Before the fault, the voltage was increased from 14.1 kV to 17.6 kV (25%). According to the transformer design, this means that one of the sections is affected at a rate of 12 seconds per layer. The initial conversion ratio was 120 and changed to 150 prior to the occurrence of the fault. That is, the transformer explosion happened after that was damaged 25% of the

primary winding. The energy stored in the internal failure of the PT was large enough to produce the explosion of the transformer and the spread of the arc.
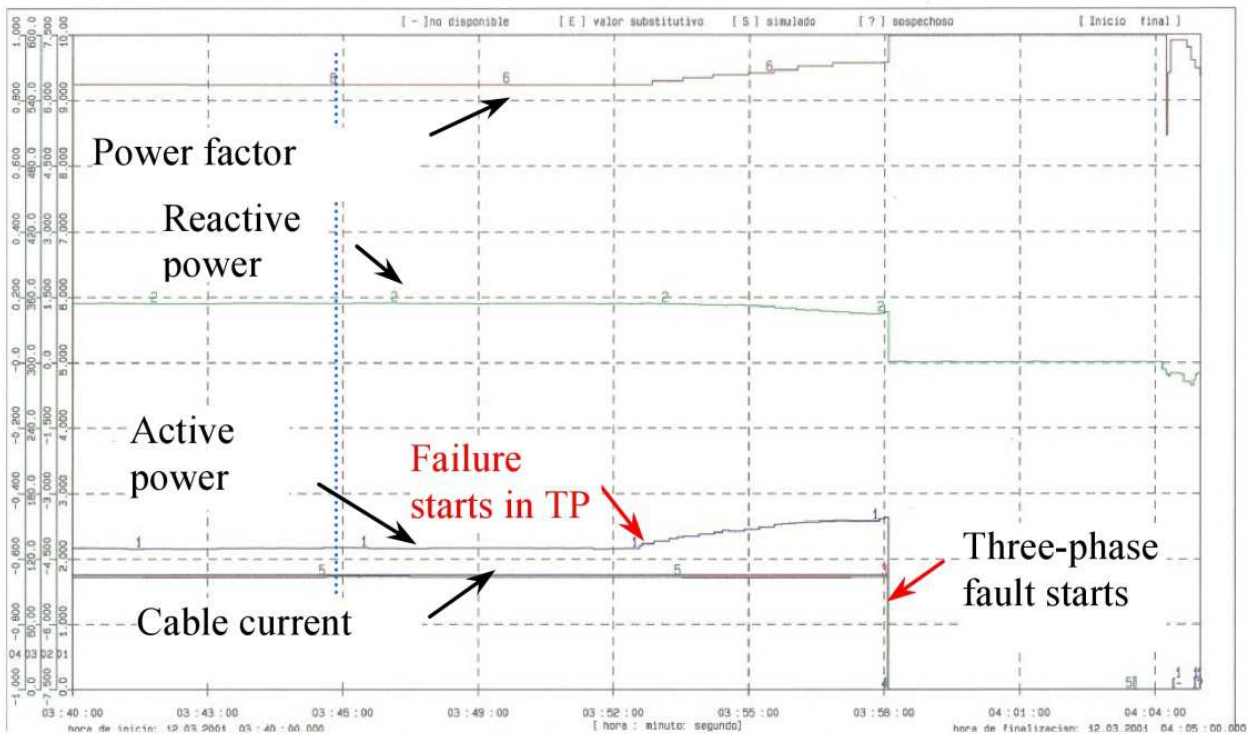


Fig. 4.3.1.1. Signals recorded of the feeder in the switchgear where the PT was installed.

Due to the open delta connection of PT's, it follows that the switchgear fire was started by the failure phase (between phases 2 and 3) of PT. According to the records of the fault currents, it is estimated that this event had duration of about 2 cycles (see Fig. 25). As shown in the figure, because the fault is a fault-phase, unbalanced residual current is generated through the common point of the current transformers. From the oscillograms it is concluded that the evolution of biphasic failure to three-phase fault was about 30 to 40 ms.

The electric arc between phases began in the TP that connects stages 2 and 3 of the switchgear. Subsequently, the arc evolves to cause the failure of phase 1 to generate a three-phase fault. Under these conditions, the arc length is estimated in the order of 60 cm. The arc is very unstable so a fire can easily spread through the fiberglass bulkheads separating the panels and the different switchgear cubicles.

Thus, according to the sequence of events leading to the occurrence of the fault, it is determined that the process of failure of a PT is a slow process, in the order of 5 to 10 minutes. However, the energy stored during this time causes serious consequences.
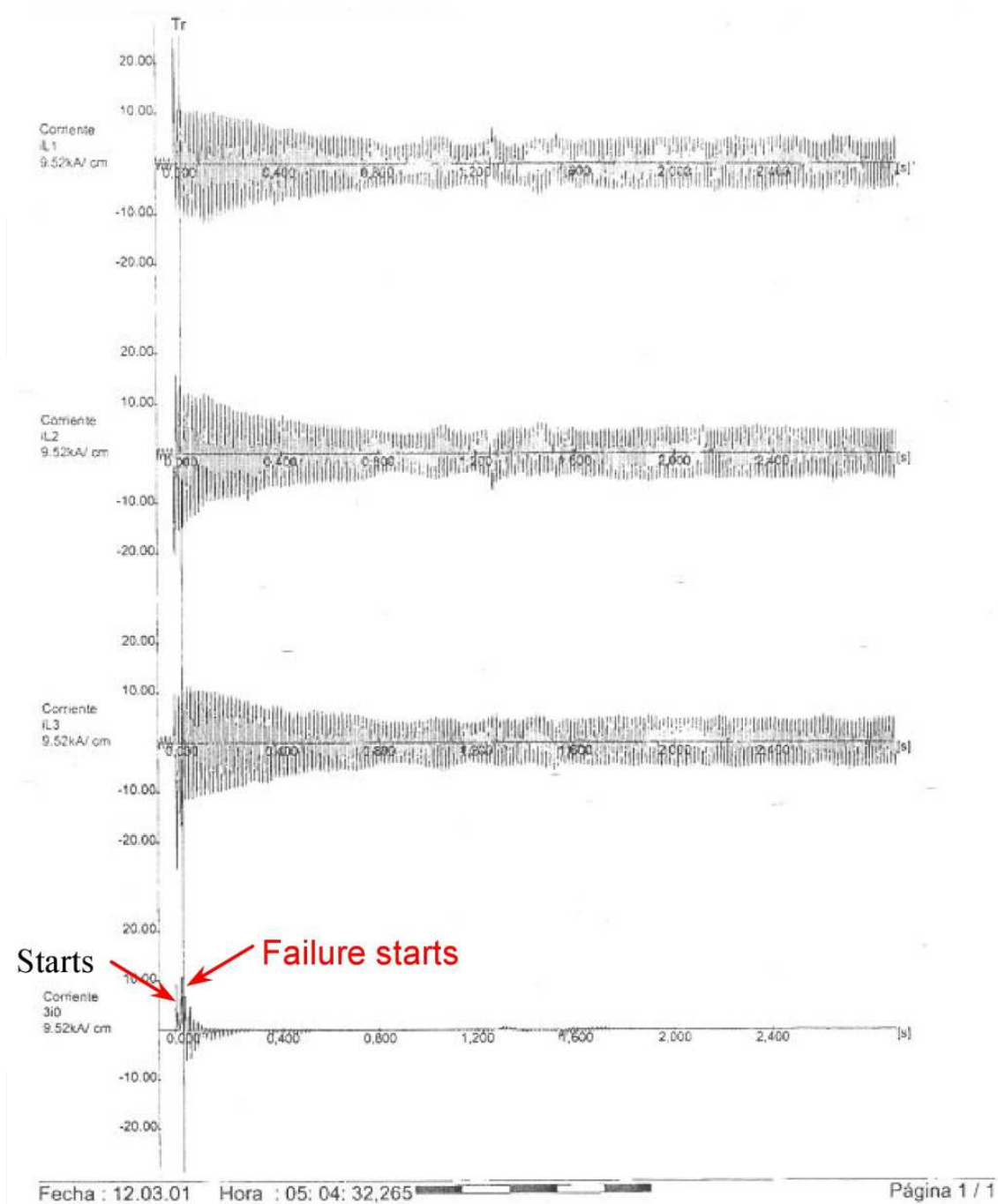
Fig. 4.3.1.2. Current signals recorded in the generator during the fault of the switchgear.

### 4.3.2 Design of PT

The failed PT had a capacity of 275 VA, therefore, the rated current of high voltage winding is limited to about 30 mA. To be connected in open delta, the level of its primary winding voltage is 14,400 V and the secondary winding is 120 V.

The failure of a PT can be started as a short circuit between turns or between rounds in the section of the primary winding of the transformer (see Fig. 4.3.2.1). The fault between turns can be maintained for a period of 5 to 10 minutes, until the pressure built up by the

insulation decomposition gases cause the explosion of the PT. This event causes mainly the carbonization of insulation and the generation of an arc between phases.

An inspection at the failed PT indicated some manufacturing defects. Due to the arrangement used for the construction of the windings do not have adequate penetration of the resin between layers. This produces cavities between layers and therefore high levels of partial discharges.



Fig. 4.3.2.1. Potential transformer that caused the failure in switchgear.

The arrangement of the windings of the PT is shown in Fig. 4.3.2.2. Each different sections of the primary winding is made of 31 AWG wire, whose capacity for maximum current is 0.160 A, with a resistance of 435 $\Omega$ / km. Each section consists of 55 layers and 200 turns per layer so that it has an electrical gradient of about 130 V per layer. Between each layer exists one or two layers of insulating paper impregnated with varnish. It has 3 metal screens (brass) placed in different areas, which are not only used to obtain a uniform distribution of the electric field inside the PT, but also serve as a connection between the different windings.

The secondary winding is isolated from the primary winding with a section of paper based on insulation and resin, with a cross section of about 7 mm. The secondary winding is formed with 16 AWG wire, whose current capacity is 6 A. This winding is made of two layers, the upper with 93 turns and the lower with 99. Between these layers are placed a paper based on insulation and varnish.

The core of the PT is covered with cardboard. It is estimated that this arrangement is used to absorb the mechanical stresses (expansion and contraction of materials) produced during the curing of the resin. This will reduce the possibility of fracture of the encapsulation of PT.

It was detected a manufacturing defect in the high voltage windings of PT. In the section that connects the terminal P2, shows a surplus of winding and insulating material in a way peak. That is, the coil is not parallel to the core, which causes the protruding part of the coil winding.

On the other hand, as a mechanism of protection for the PT's are generally used fuses of 2 A in the high voltage side. However, this protection is only suitable for the case of full ground faults in PT, and prevents internal short circuits in the windings of the transformer.

As noted in the records of power system switchgear the failure was caused by the fault between turns of the primary winding of the PT. The most critical condition occurred at the instant it had damaged 25% of the primary winding of the PT, in which case the maximum current that could flow through this winding would be about 45 mA. It is noted that this magnitude of current is very small, and therefore the fault cannot be detected by the fuses installed in the PT.
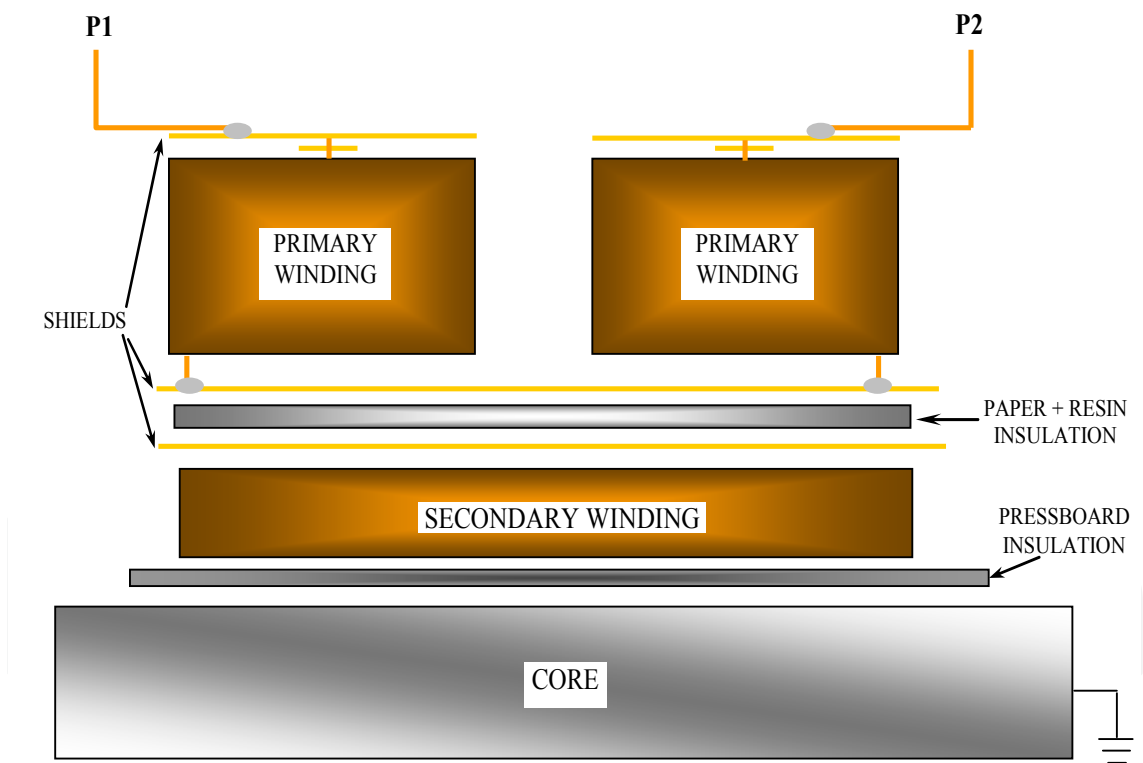


Fig. 4.3.2.2. Schematic design of PT.

### 4.3.3 Destruction of the switchgear as a result of the failure of PT

One of the causes that led the destruction of the switchgear was the materials currently used in it, which contributed to the rapid spread of fire. The switchgear was metal-enclosed type, in which the manufacturer used fiberglass spacers bonded to the separation between the phases of the switches and the separation between panels. This material (fiberglass) is

highly flammable, so that the arc fault produced by PT caused instantaneously the fire in panel separators.

The temperature produced by the arc is very high (around 10,000 - 20,000 K). Therefore it only takes a few milliseconds to melt the materials installed on switchgear. If the switchgear does not have a fire fighting system and the failure continues to be powered by the generator, the fire may spread to the rest of the panels [ABB].

Fig. 4.3.3.1 shows the relationship between arc duration and damage in different materials of the switchgear. This figure shows that from the 500 ms the damage caused by the arc can be considered catastrophic.
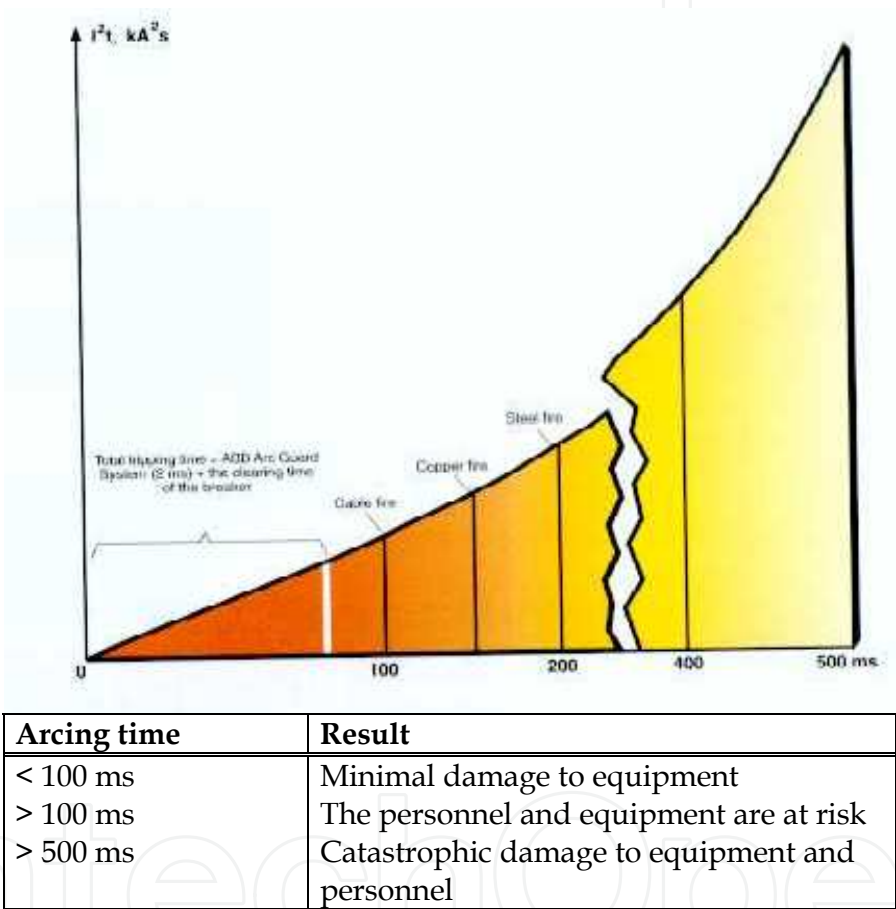


| Arcing time | Result |
|---|---|
| < 100 ms | Minimal damage to equipment |
| > 100 ms | The personnel and equipment are at risk |
| > 500 ms | Catastrophic damage to equipment and personnel |

Fig. 4.3.3.1. Graph damage caused by an arc of power versus time.

## 4.4 Solution to the problem

To avoid the resonance phenomenon in the PT's there are two alternative solutions that are mentioned below.

### 4.4.1 Winding wye connection of PT

To solve the problem of series resonance presented in open delta connection the PT windings can be connected in grounded wye. This connection limits the possibility of occurrence of the phenomenon of resonance, because only the parasitic capacitance of the

transformer is presented. Fig. 4.4.1.1, shows the arrangement of PT grounded wye connection. As shown in Fig. 4.4.1.1, if a fault occurs at point F in one phase, it is not possible that series resonance occur in the circuit, because one end of the primary winding of the PT is grounded.

When a failure occurs in the grounded wye connection of PT's, the fuse will act protecting the PT. It is necessary to prevent failures that may arise between phases to prevent arcing that could ignite the switchgear. It is necessary to install non-flammable separators between the panels of the switchgears to prevent fires from spreading to other panels.
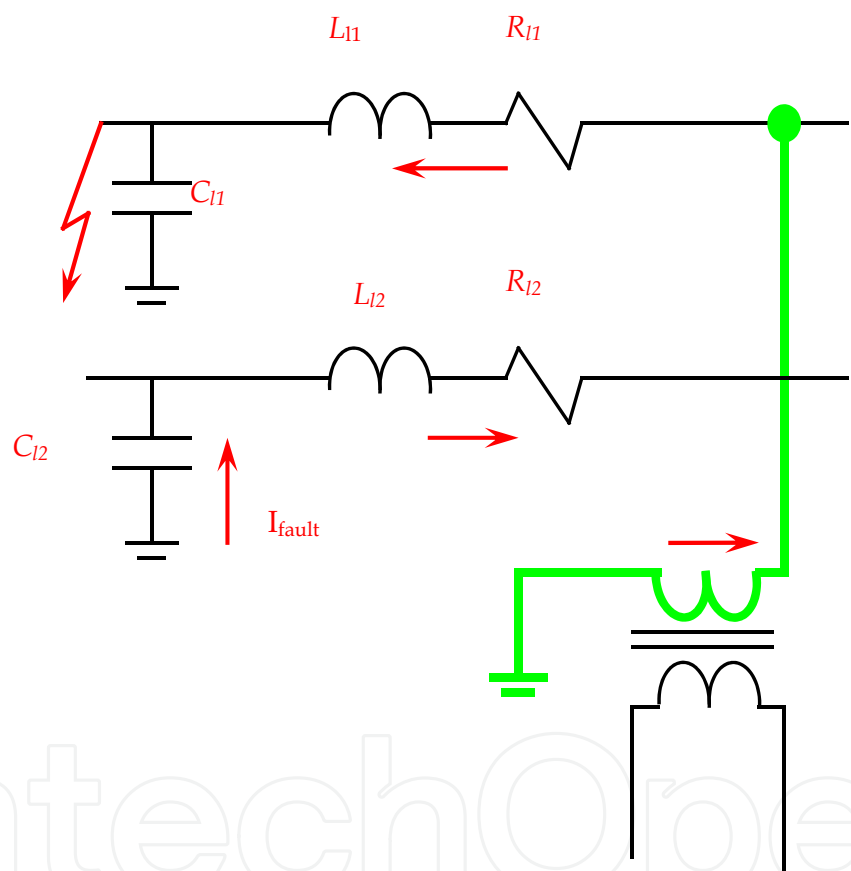


Fig. 4.4.1.1. Circuit connecting a grounded wye PT.

### 4.4.2 Implementation of disconnector link

Another way to avoid damage in switchgears due to faulty PT's is installing disconnects under load conditions in each of the phases of the open delta, see Fig. 4.4.2.1. Since the failure process is slow it can be detected through a relay to operate as a differential voltage and sent a signal to open a disconnect. This change is easy to implement in new switchgears and requires a specific analysis for each switchgear due to the fault currents that may arise in each.
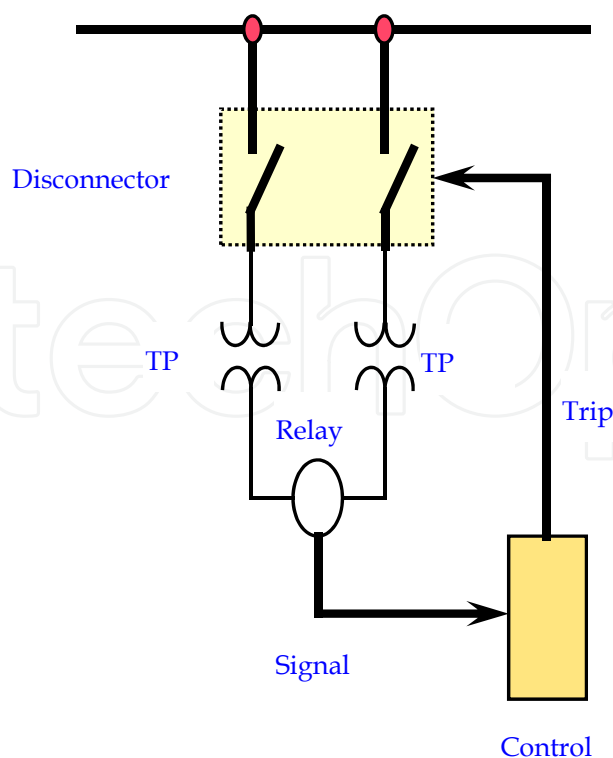
Fig. 4.4.2.1. Connection of disconnector link under load conditions in open delta PT's winding ircuit connecting a grounded wye PT.

## 5. Conclusion

The low resistance neutral grounding scheme at just one source of generation in industrial power systems creates favorable conditions for resonance overvoltages.

The TP's are probably the most susceptible to failure when they are operating in open delta connection, because it is feasible to generate faults between phases with relative ease.

The resonance faults occurred in specific places of the network where the concentrate parameters of capacitance and inductance are tuning at resonance frequency and not precisely the weak point of the system.

Resonance overvoltages can be avoided by the use of a proper grounding method. All energy sources, generator and transformer, must be grounded. It is necessary to consider the protection scheme and the interconnection´s characteristics of the electrical power equipments to avoid failures.

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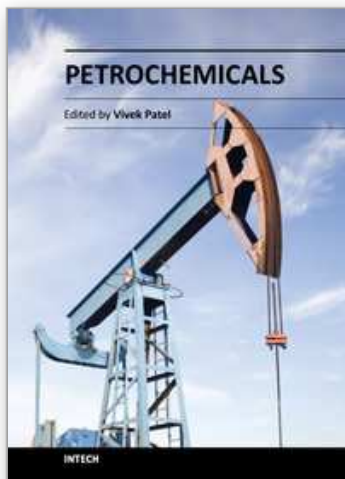
**Petrochemicals**

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The petrochemical industry is an important constituent in our pursuit of economic growth, employment generation and basic needs. It is a huge field that encompasses many commercial chemicals and polymers. This book is designed to help the reader, particularly students and researchers of petroleum science and engineering, understand the mechanics and techniques. The selection of topics addressed and the examples, tables and graphs used to illustrate them are governed, to a large extent, by the fact that this book is aimed primarily at the petroleum science and engineering technologist. This book is must-read material for students, engineers, and researchers working in the petrochemical and petroleum area. It gives a valuable and cost-effective insight into the relevant mechanisms and chemical reactions. The book aims to be concise, self-explanatory and informative.