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Applying Frequency Response Method for Contact Rails Fault Diagnosing in Ungrounded Electrical Railway System

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ABSTRACT

General faults in regular electric railway systems can be detected by implementing the specific protection functions such as ground fault or sensitive earth fault. Otherwise, in ungrounded electric railway systems which are using both feeding and return contact rails at the same time, fault detection cannot be performed with the above-mentioned function. Due to recent growth in electric railway networks especially in metropolises, it is an essential requirement to improve operation and safety indexes by using efficient fault preventing and fault clearing method in minimum time.

In this research, a new fault diagnosing method is developed by using frequency response of contact rail system. This technique is based on observing pattern changes that are caused by some expected faults such as the broken contact rail, contact rail to ground faults on feed or return circuit frequency response.

1. Introduction

In traction power supply networks (TPSN), overhead centenary lines or contact rails transfer electrical energy between traction substation and trains. There are various configurations of transmission network with different conductors, current return system and various nominal voltages. TPSN exhibits many electrical properties, where the most common properties are nominal voltage, current, electrical resistance, inductance and capacitance. The last three parameters are inherent characteristics of atypical TPSN and depend on the network configuration itself. Furthermore, they are important in the development of power network models that are used in power system analysis.

In this research, resistance (R), inductance (L) and capacitance (C) of a typical ungrounded TPSN is used to develop a novel fault diagnosing method (FDM). This method could be explained in three simplified steps:

- Calculation of typical ungrounded TPSN parameters: R, L, and C,

- Modeling a typical ungrounded TPSN using the short representation of transmission line theorem (TLT)

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- Applying FDM using generated TLT model.

2. Calculation of typical TPSN parameters

Nowadays, analytical method is commonly used to calculate the inductance and capacitance of many transmission line configurations. The advantage of using analytical method is the physical interpretation of inductance and in the fact that the capacitance equations in transmission line is clear and well defined.

General assumptions made for calculating inductance of transmission lines are:

a) The cross section of TPSN is uniform

b) The current and charge densities are uniform over the entire length of conductors

c) The conductivity, permittivity and permeability over the entire length of conductors are constant

In this paper, a double monorail track as an ungrounded TPSN is studied, Figure 1. The related resistance, inductance and capacitance between two parallel-ungrounded monorail tracks, are obtained in following sections [1, 2].

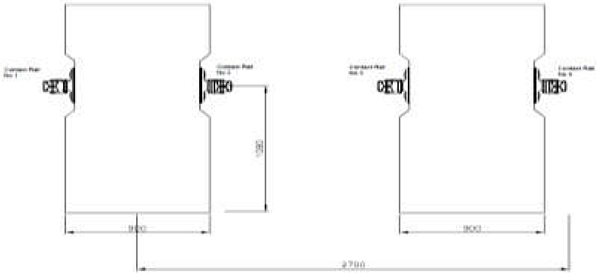

Figure 1. A typical monorail rout supplied with ungrounded TPSN

In simple words, this TPSN will be defined by means of the parameters such as the resistance, inductance, capacitance and conductance. Here, it is not intended to derive the formulas rather to develop some concepts about the TPSN parameters. It will help to understand the TPSN modeling and in analyzing the power system.

In this section, the line resistance and inductance are discussed. In the next part, the line capacitance and conductance are explained**.**

2.1. Resistance

The conductors of the transmission lines have small resistance [3]. For short lines, resistance plays an important role. As the line current increases so do the ohmic loss (RI^2 loss). When the current exceeds a certain value the heat generated due to ohmic loss starts to melt the conductor and the conductor becomes longer. This in turn results in more sag. The current at this condition of conductor is irreversible and is called the thermal limit of conductor. Short overhead lines should be operated well within this limit.

Ungrounded TPSN usually use polygon conductor rails, which are divided in many expansion sections, by using the expansion joints. Therefore, the actual length of the conductor is about 2 % more than the normal straight conductor length. Consequently, from the above formula, the resistance of the TPSN is proportionally 2% more than the conductor length [4]. Another important factor is that when an alternative current (AC) with specific frequency is applied in TPSN, the current density increases towards the surface of the conductor and current density at the center of conductor is decreased. That means the major part of the current flows towards the surface of conductor namely the "skin effect". Then the effective cross sectional area of the conductor reduces at the power frequency (50 Hz) and therefore, the conductor resistance increases in higher frequency. Therefore, the AC resistance of conductor is more than the DC resistance.

Temperature is another factor that influences the resistance of conductor. The resistance varies linearly with temperature and is determined by the manufacturer's specification.

2.2. Inductance

For medium and long distance TPSN, the network inductance (reactance) is more dominant than resistance [5]. It is known that a magnetic field is associated with a current carrying conductor. In AC TPSN, this current varies sinusoidally, so the associated magnetic field is proportional to the current and varies sinusoidally. This varying magnetic field induces an emf (or induced voltage) in the conductor. This emf (or voltage) opposes the current flow in the network. This emf is equivalently shown by a parameter known as inductance. The inductance value depends upon the relative configuration between the conductor and magnetic field. Inductance in simple language is the flux linking with the conductor divided by the current flowing in the conductor. In the calculation of inductance the flux inside and outside of the conductor are both are be considered. The inductance so obtained is the total inductance. From this point on if not exclusively mentioned then inductance means the total inductance due to conductor internal and external flux linkages. Manufactures usually specify inductance value per kilometer or mile [5,6].

For a TPSN consisting of a single-phase line (see Figure 2), the conductor inductance is:

$$L = 2 \times 10^{-7} \ln(\frac{D}{r1'}) \tag{1}$$

Where D is the distance between the centers of conductors and $r1'$ is the apparent radius, which derived as:

$$r1' = r1 \times e^{-\left(\frac{1}{4}\right)} = 0.7788 \text{ r1} \tag{2}$$

Here, r is the actual radius of conductor or equivalent radius of surrounding circle of a specified conductor.

For this single phase TPSN, the return path also has the inductance, L'. If the return conductor is of radius r2, then:

$$L' = 2 \times 10^{-7} \ln(\frac{D}{r2'}) \tag{3}$$

Therefore, the total inductance of single-phase circuit obtained from following equation:

$$Lt = L + L' = 4 \times 10^{-7} ln(\frac{D}{\sqrt{r'1r'2}}) \tag{4}$$

In this research, a double track ungrounded TPSN is studied. Therefore, considering the configuration that is presented in Figure 1, the related inductance can be derived as:

$$L = 2 \times 10^{-7} \ln(\frac{GMD}{GMR}) \tag{5}$$

Where

$$GMD = \sqrt[3]{D_1 . D_2 . D_3} \tag{6}$$

$$GMR = \sqrt[3]{r'_1 . r'_2 . r'_3} \xrightarrow{r'_1 = r'_2 = r'_3 = r'} GMR = r'$$

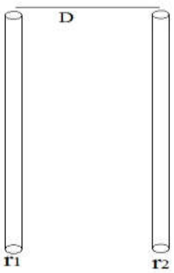

Figure 2. A TPSN consist of a single-phase line and return conductor

2.3. Capacitance

It is already mentioned that the leakage current flows between the transmission lines and the ground and between the phase conductors. Leakage current flows to ground through the surface of insulator. This leakage current depends upon the suspended particles in the air, which deposit on the insulator surface. It depends on the atmospheric condition. The other leakage current flows between the phases conductors due to the occurrence of corona. This leakage current also depends upon the atmospheric condition and the extent of ionization of air between the conductors due to corona effect.

Both these two are quite unpredictable and no reliable formula exists to tackle these leakage currents [7,8]. Luckily, these two types of leakage currents are negligibly small and their ignorance has not proved to influence much the power system analysis for line voltage and current relationships. Here, the leakage currents are ignored therefore the leakage resistance will not be shown. The inverse of this leakage resistance is called the line conductance.

The rest of the article is about the line capacitance. Like the previous article on the inductance, it is not also intended to derive the formulas for the capacitance for different line configurations rather to develop some concepts. As the flow of line current is associated with inductance, similarly the voltage difference between the two points is associated with the capacitance. Inductance is associated with magnetic field and capacitance is associated with the electric field.

The voltage difference between the phase conductors gives rise to an electric field between the conductors (see Figure 3). The two conductors are just like parallel plates and the air in between the conductors is dielectric. Consequently, this arrangement of conductors gives rise to capacitance between the conductors.

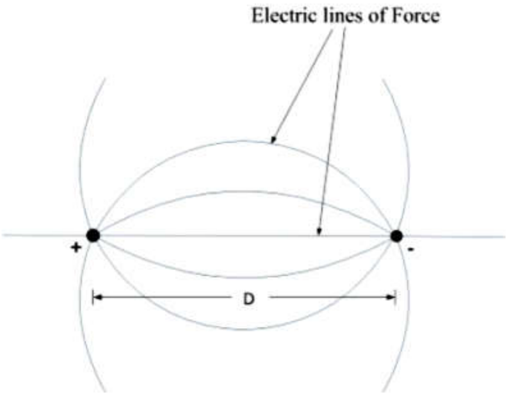

Figure 3. A TPSN consist of a single phase line

3. Modeling a typical ungrounded TPSN using the short representation of transmission line theorem (TLT)

At a glance, transmission line theorem (TLT) introduce transmission lines as a complex system which is characterized by a series resistance, inductance, and shunt capacitance per unit length. These values determine the electrical performance of the transmission line and the voltage drop across it at full load.

In this modeling, a typical ungrounded TPSN of 20 km length is considered. Each 400 m is represented by a partial pi model with R and L in series and two C/2 in parallel. Figure 4 shows a schematic illustration of TLT.

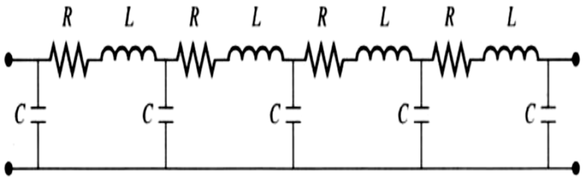

Figure 4. A simplified representation of TLT

Regarding the derived formulas in previous sections of this article all required R, C and L properties of a typical ungrounded TPSN can be calculated. Table 1 shows the necessary coefficient for calculating TLT model variables.

As a result, the calculated R, L and C parameters of the above mentioned typical TPSN are:

R=0.02 [Ω/km]

L= 8.24 x 10-4 [H/km]

C=1.05 x 10-8 [F/km]

Table 1. Design parameters of an ungrounded TPSN

Item	Description	Value
ρ	Electrical resistivity	1.7 x 10^{-8}[Ω/m]
ε	Electrical permittivity	8.85 x 10^{-12}[F/m]
A	Cross section of a contact rail	4500 [mm^2]
D	Distance between two parallel adjacent positive and negative conductors	2.7[m]
D’	Distance between two parallel positive conductors	0.9 [m]
r	Radius of surrounding circle of a specified conductor	0.027 [m]

4. Applying FDM using the above generated TLT model

In addition, of an analytical method with realistic parameters; it is necessary to define specific fault scenarios for evaluating the proposed FDM. Regarding practical experiments in under operation traction network, the following scenarios can be analyzed:

- Normal network configuration,
- Minor leakage fault in insulation supports for example: increasing in leakage current due to pollution absorption at insulation support,
- Major leakage fault in insulation support such as a positive contact rail to ground fault
- Minor crack in contact rail
- Major crack in contact rail

In this section, the proposed frequency response FDM will be applied in the above setups by means of MATLAB Simulink software environment. Figure 5 shows the proposed simplified Simulink model that is used for calculating and taking snapshot of TPSN frequency response.

In this Simulink model; in addition to TLT model, two resistances are considered. The first one shows the internal resistance of a controlled pulse generator and the second one represents the calibration resistance.

Calibration resistance is used to tune the frequency response of the proposed model to aim at more accurate and particular response for FDM proposes. In this research, the Simulink model is developed with a setup m-file which is used for setting up the case study with R, L and C parameters and also for analyzing the results. The produced results in Simulink model, are collected and sent to the workspace with a structure that facilitates to have the values and their associated time characteristic at the same time, in each studied scenario.

Subsequently, a normalized frequency response is calculated. Normalization of that frequency reply allows a precise study, which is focused on the TPSN model, on each scenario. This form of FDM is based on comparing the pattern of the achieved frequency response in each scenario with a normal frequency reply of the model. Frequency response of ungrounded TPSN in normal network configuration is shown in Figure 6.

The normalized frequency response of the intended ungrounded TPSN when a minor leakage fault occurs in insulation supports is shown in Figure 7. As an example, this fault can happen once the leakage current is increased due to the pollution absorption at the insulation support.

Not having cleared the above minor fault, can result in a serious TPSN damage that has a frequency response pattern as illustrated in Figure 8.

Another regular minor fault in TPSN is the minor crack in the contact rail. This kind of malfunction can be caused by an extraordinary contact between the collective shoes of a passing train and the fixed contact rails. Another reason can be the aging effect of a long operation period. Figure 9 shows the associated frequency response in this case.

The passing speed of a train at ungrounded TPSN may be 120 km/h. Due to the huge mass of this train (approximetly 200 tons); the related kinematic energy of the train will be more than $1.1\text{x}10^{12}$ J.

This amount of kinematic energy can easily break the contact rails. Normaly TPSN includes long contact rails and a broken contact rail may stay hidden untile a serious power system or rolling stock damage happens. Figure 10 shows the related frequency response in this case which can not be accidentally overlooked.

The fault diagnosing method, which is introduced in this research, used the above frequency pattern as TPSN index in each study scenario. In brief, any changes at TPSN inherent parameter makes a significant deviation in the frequency response. As a result, diagnosing of each type of the fault will be possible by means of the frequency response analysis.

There are two important characteristics that are associated with the faults including the type and the severity. The summary in Table 2, shows the principles of the proposed FDM method.

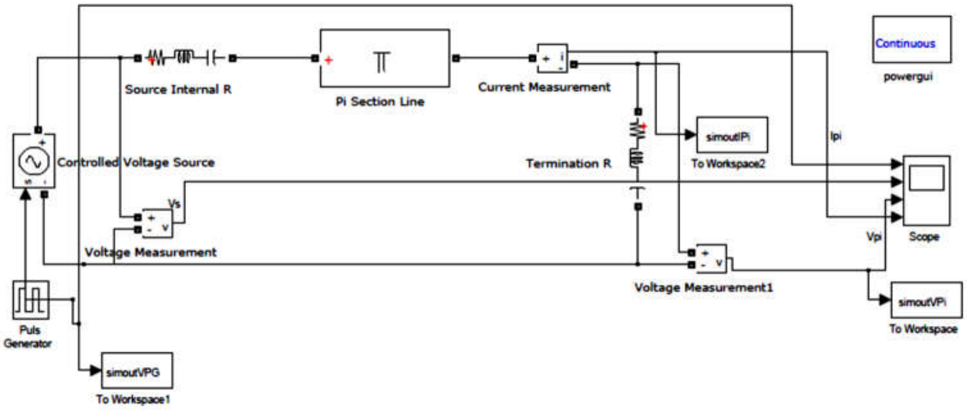

Figure 5. Proposed simplified Simulink model of a typical ungrounded TPSN

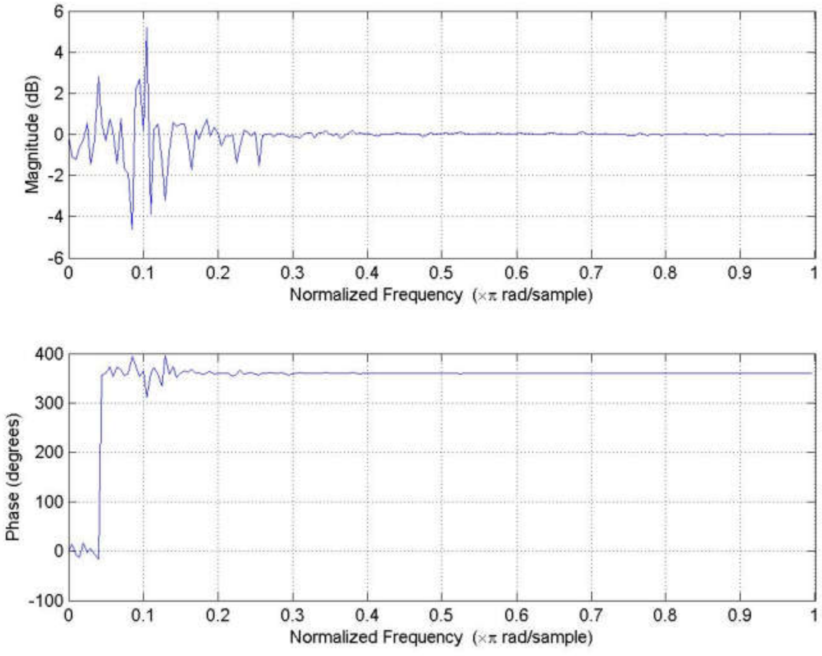

Figure 6. Frequency response of ungrounded TPSN in normal network configuration

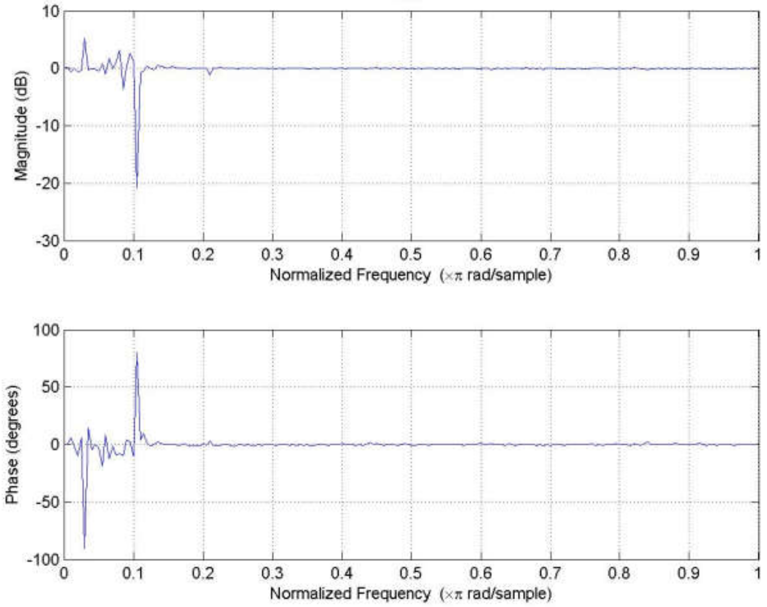

Figure 7. Studied ungrounded TPSN frequency response in minor leakage fault in insulation supports

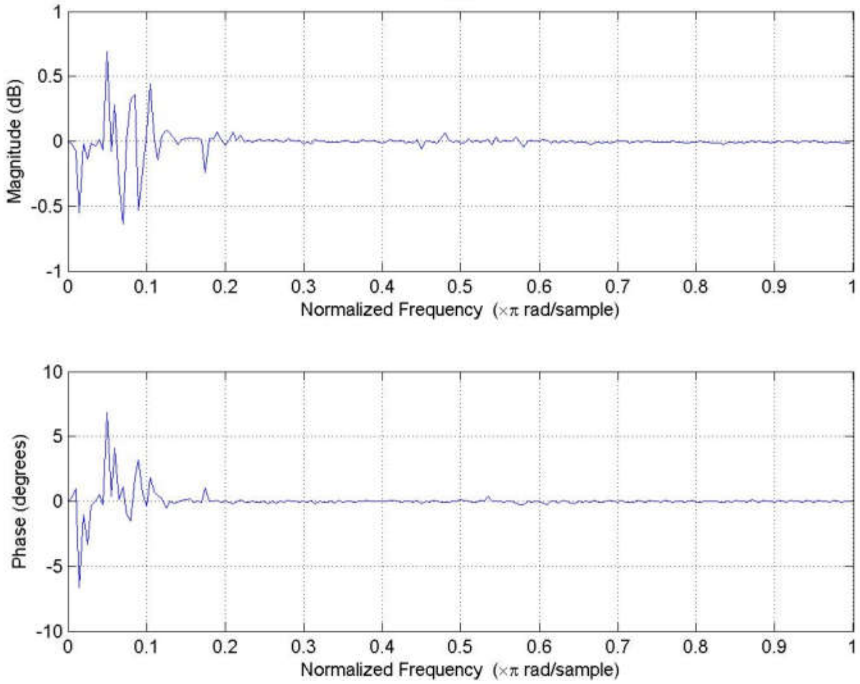

Figure 8. Frequency response of ungrounded TPSN in major leakage fault in insulation support

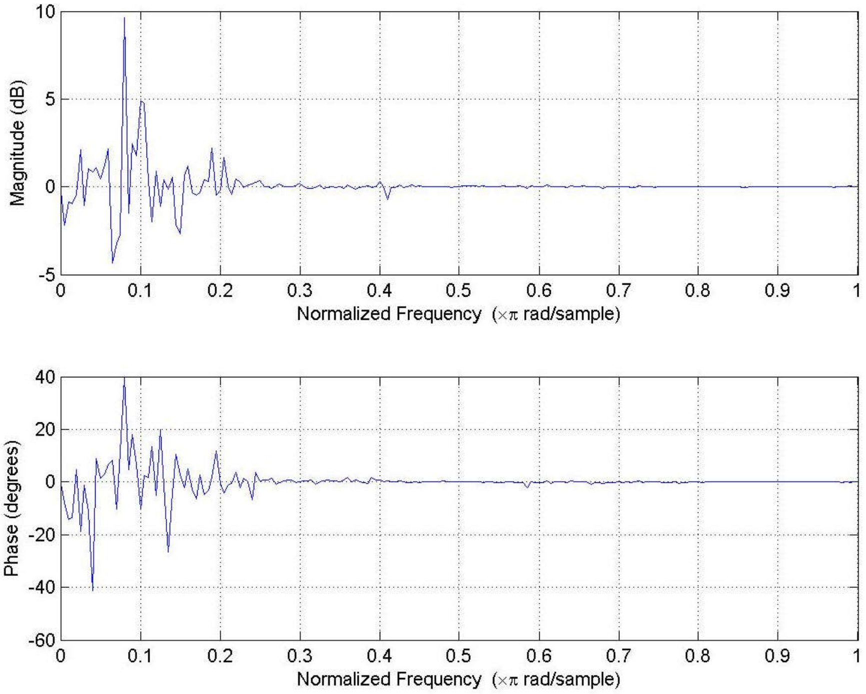

Figure 9. Frequency response of ungrounded TPSN in minor crack in contact rail

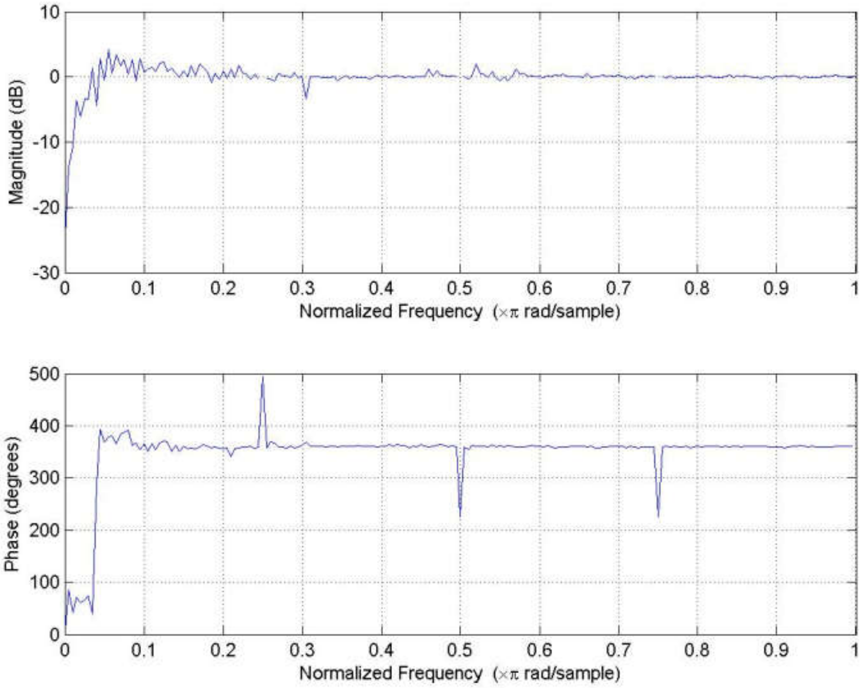

Figure 10. Frequency response of ungrounded TPSN in major crack in contact rail

Table 2. FDM summarized look up table

Fault category	Description	Frequency response pattern changes in normalized frequency	
		Magnitude [dB]	Phase[degree]
No fault	Normal configuration	Rang : [-4.5 5.5] Mean$_{steady}$: 0	Rang : [-10° 400°] Mean$_{steady}$: 360°
Insulation fault	minor leakage fault in insulation support	Rang : [-21 6] Mean$_{steady}$: 0	Rang : [-90° 80°] Mean$_{steady}$: 0°
	major leakage fault in insulation support	Rang : [-0.6 0.7] Mean$_{steady}$: 0	Rang : [-6 ° 7°] Mean$_{steady}$: 0°
Conductor break down	minor crack in contact rail	Rang : [-4 9.8] Mean$_{steady}$: 0	Rang : [-40 ° 40 °] Mean$_{steady}$: 0°
	major crack in contact rail	Rang : [-25 4] Mean$_{steady}$: 0	Rang : [20 ° 500 °] Mean$_{steady}$:360°

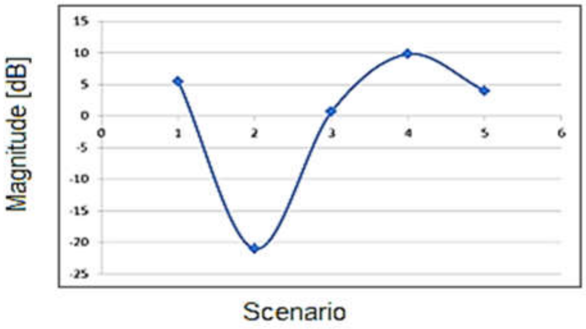

Figure 11. Trajectory of magnitude state transform in various scenario

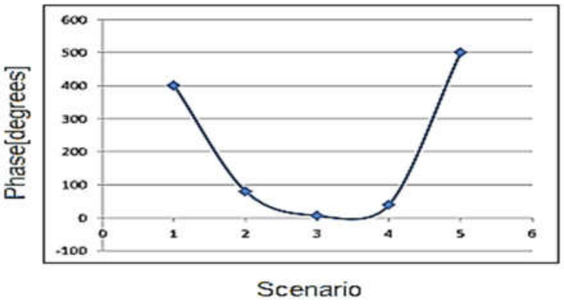

Figure 12. Trajectory of phase state transform in various scenarios

A novel way to illustrate the state transform of ungrounded TPSN is drawing each mode of frequency response as an indexed extreme point. Figure 11 and Figure 12 shows the state transform pattern in magnitude and phases of the calculated frequency responses.

5. Conclusions

The Fault Diagnosis Method (FDM) that is developed in this research shows the simplicity and efficiency of frequency response analysis. As mentioned in the above sections, this FDM is effective because various types and ranges of faults in ungrounded TPSN can be detected and it is easy to use them due to the proposed visual pattern recognition. Precise analysis of FDM results in Table 2, Figure 11 and Figure 12 shows that the leakage fault in ungrounded TPSN makes a significant decrease in the magnitude and phase indexed points of frequency response trajectory. Whereas, any fault in conductor rail section such as the partial breakdown, will cause an important increase in that trajectory. This gives an effectiveness criterion for detecting and discrimination of regular faults in contact rails of TPSN.

This paper is also recommending further research work on other analytical method for evaluating ungrounded traction power supply frequency response in different operation scenario by means of mathematical pattern recognition analysis.

Furthermore, other modeling and simulation topology can be developed to calculate more precise frequency response of ungrounded TPSN.

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