Definition of a New Graphic Pattern for Single Phase to Ground Fault in the Power Plant and Effects of the Neutral Grounding Impedance on It

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***Abstract*— The grounding system of the step-up transformers is one of the main issues in power networks. The dynamic behavior of the generators is affected at fault duration by the neutral grounding impedance. In this paper, at first analytical expressions of some parameters such as current, active power, and power angle of the generator are derived for a phase to ground fault. Then the validation of derived equations is examined by simulation of a local real power network. At last, these equations will be used to define a new graphic pattern of fault which is the locus of the active power vs short circuit current. The shape of this pattern is related to the type of fault and grounding impedance. Hence it can be used to identify some faults in the power systems.**

***Keywords*— graphic pattern, grounding system, ground fault**

I. INTRODUCTION

The generation and transmission voltages in petrochemical industries are generally medium levels. The main electric fault in these industries is the line to ground (LG) fault. Because of explosive and flammable chemical units and the harm of stopping the production process, it is necessary to provide a low-level fault current.

In a solidly grounded system, the short circuit current is high. But healthy phases face with a little over-voltage. Increasing the grounding impedance leads to decreasing the current fault and increasing the overvoltage value of healthy phases. Using grounding impedance in the neutral point of transformers is one of the main methods to limit the fault current level.

Generally, the studies of the grounding system are divided into three main categories. The first issue is the neutral point grounding calculation procedure and its effects on the power system parameters. Some researches regarding these subjects are as follows.

In [1], the design procedure of a low impedance neutral grounding system for a real network is explained. The calculation procedure of the neutral grounding resistor (NGR) for step-up transformers of a petrochemical complex can also be found in [2]. Following the previous paper, the effects of various NGOs on the stability of the power system of a petrochemical complex and the voltage unbalances under the existence of different grounding systems have been compared in [3]. The application and effects of high resistance grounding on the voltage drop have been analyzed in [4-5] for a medium voltage level power system. Another impact of ground resistance on EHV transmission lines is on the arc current, which has been considered in [6]. The general considerations and differences between grounding systems of overhead lines and underground cables are declared in [7]. A thyristor-based controllable reactor which used to ground the neutral point of a power transformer introduced in [8].

Other issues related to grounding systems include the earth fault calculation and location. For example, in [9] a simple criterion for locating the symmetric and asymmetric faults based on the ratio between zero sequence and positive sequence impedances has been presented. Another method for locating the line to ground faults is the calculation of zero sequence current which is proposed in [10]. The sensitivity analysis of a single-phase to ground fault system in connection with high impedance faults has been done in [11].

In [12] the design and implementation of a hardware simulator for understanding concepts phase and ground fault protection system, evaluate the maximum of short circuit current prospective in the simulator for safe operation, and describe the mechanism of the relay protection operation related to the symmetrical fault and asymmetrical fault disturbance, has been described.

The third common issue about the neutral grounding impedances is the protection considerations related to the grounding system. For example, distance relays' proper operation is related to the transient resistance of line to ground fault. This resistance varies with the grounding impedance and causes relay malfunctioning. This problem and its solution have been examined in [13]. An efficient relaying strategy for line-to-ground faults in the indirectly grounded system was introduced in [14]. In [15] the protection and improvement of a mining resistance grounding system have been considered. In this system, the neutral point is grounded via a small resistance. Finally, in [16], a method to protect the power system has been introduced by monitoring the grounding resistance.

One method to identify the fault is the definition of a pattern to some parameters. For example, in [17] a function for surge impedance to identify double earth fault in power systems was introduced. Or [18] by the ratio of the negative sequence of voltage magnitude at two ends of lines estimates the fault location. This method is not limited to studies of power

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systems and is used in many types of research such as electric machines [19] etc.

Despite all studies about the neutral point grounding systems, the effect of the grounding system on generator behavior, its power angle, and the local dynamic loads (such as electric motors) have not been seriously considered so far.

This paper intends to do a perfect analysis of the effects of the type of grounding impedance (resistor or reactor) and its value on the main characteristics of a power plant. Also, a new graphic pattern will be introduced, which can be used to identify the line to ground fault under different grounding conditions of the neutral point of the main transformer. To this end, the paper is organized as follows: In section II, a simple electric circuit is used to model a line to ground fault. Then the analytical expressions of some parameters such as current, active power, and power angle of the generator are derived for a phase to ground fault. Validation of derived equations is examined by simulation of a real power plant located in a petrochemical complex in section III. In section IV, these equations will define a new graphic pattern of fault that presents the locus of active power vs. short circuit current. The shape of this locus is related to the type of fault and grounding impedance. At last, the conclusion of the paper is presented in section V.

II. ANALYTIC CALCULATION OF LG FAULT

A. CALCULATION OF FAULT CURRENT

A simple model of a thermal power plant is shown in Figure 1. This model consists of a synchronous generator and step-up power transformers with output feeders. The winding connection of the transformer is assumed as d-Y. The neutral point of the star connection has been grounded with impedance Zn. This impedance may be resistance or reactance. In addition to type, its value will change during this study. Statistic studies show that most electrical faults in a petrochemical complex are single phase to the ground fault, which occurs in the output feeders of the main transformers. Therefore, the place of fault occurrence is considered the point P in Figure 1. All the three circuits of zero, positive and negative sequences are connected in a single-phase to ground fault. In this case, the fault current path can be modeled by an ohm-inductive circuit as shown in Figure 2. In this circuit, R and L represent all resistances and inductances in the fault current path, including impedance of all components and grounding system, respectively, and the voltage source represents the generator. The value of current in this circuit can be calculated as follow.

$$I_{sc} = \frac{U}{|Z|}\left[\sin(\omega t + \varphi - \theta) - \sin(\varphi - \theta)e^{-R/_{L}t}\right] \qquad (1)$$

Where $Z = \sqrt{R^2 + (\omega L)^2}$, $\theta = tan^{-1}\frac{\omega L}{R}$, $\omega = 2\pi f$. This relation is used to analyze the discussed issue. As seen in this equation, short circuit current consists of a sinusoidal steady-state current and a declined exponential component.

Increasing the resistance part of the circuit results in decreasing the current magnitude of the exponential part. On the other hand, using a reactor as grounding impedance increases the value of L in (1) and increases the exponential component's magnitude.

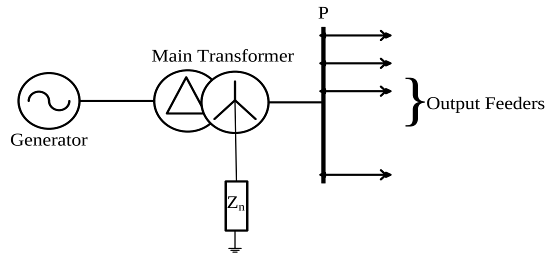


Fig.1. Schematic diagram of the unit of power plant

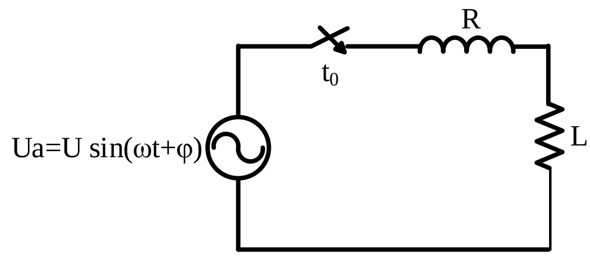


Fig.2. Equivalent Circuit for LG fault

B. CALCULATION OF GENERATOR POWER ANGLE

The swing equation can obtain the variations of the power angle of the generator. As per unit shape, the swing equation is introduced as the below equation.

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H}(P_m - P_e) \qquad (2)$$

At no-load conditions by neglecting the losses, P_e is approximately zero and equivalent with P_m. After the occurrence of LG fault, the mechanical power of the turbine is zero while the electric power (at fault duration) can be calculated as follows:

$$P_e = U_a I_a + U_b I_b + U_c I_c = U_a I_a = U_a I_{sc} \qquad (3)$$

Where $I_a = I_{sc}$ and equal to equation (1) and voltage is equal to $U_a = U\sin(\omega t + \varphi)$. The current of the healthy phases (b and c) is zero because of no-load conditions. Therefore the fault active power can be defined as follow.

$$P_e = U_a I_{sc} = U\sin(\omega t + \varphi).\ \frac{U}{|Z|}\left[\sin(\omega t + \varphi - \theta) - \sin(\varphi - \theta)\, e^{-R/_{L}t}\right] = \frac{E^2}{|Z|}\left[\frac{1}{2}\{\cos(2\omega t + 2\varphi - \theta) - cos\theta\} - \sin(\omega t + \varphi)\sin(\varphi - \theta)\, e^{-R/_{L}t}\right] \qquad (4)$$

Integration of equation (2) is led to extract the power angle variations as follows.

$$\frac{d\delta}{dt} = \frac{\pi f}{H}\int_0^t (-P_e)dt = -\frac{K}{4\omega}\sin(2\omega t + 2\varphi - \theta) - [Asin(\omega t + \varphi) + Bcos(\omega t + \varphi)]\sin(\varphi - \theta)\, e^{-R/_{L}t} + \frac{Kcos\theta}{2}t + (\frac{1}{4\omega}\sin(2\varphi - \theta) + Asin\varphi + Bcos\varphi) \qquad (5)$$

Where $= \frac{\pi f U^2}{|Z|}$, $A = \frac{LR}{R^2 + L^2}$, $B = \frac{L^2}{\omega(R^2 + L^2)}$ and t is fault duration. Although δ can be derived with the integration of this equation, because of the long term of it, it is preferred to solve numerically as follow.

$$\delta = \int_0^t \frac{d\delta}{dt}dt = \sum \frac{d\delta}{dt}\Delta t + \delta_0 \qquad (6)$$

Where δ0 is the value of power angle at fault occurrence moment and Δt is the time step of the calculation.

III. ANALYSIS OF SINGLE PHASE TO GROUND FAULT

In this section, with the simulation of a power plant, the effect of grounding impedance on power plant parameters will be analyzed to validate the derived equations in the previous section. To this end, the real data of a power plant located in a petrochemical complex will be used. The simulated system is exactly similar to the presented structure in Figure 1. At first, the neutral point of the main transformers is grounded directly without any impedance (Zn=0). There is no electric load on the generator. Therefore at normal conditions, the current and power angle of the generator is about zero. A single-phase to ground fault occurs at t=5sec and continues to t=5.2 sec. The variations of fault current are shown in Figure 3. This current is following equation (1) and formed by sinusoidal and a declined components.

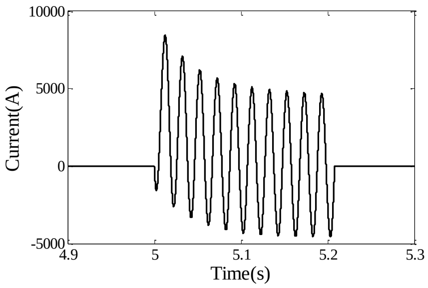
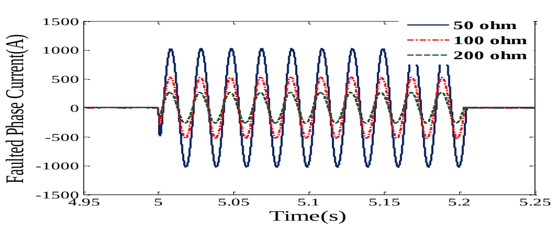


Fig.3. Fault current variations in a solidly grounded system (Zn=0)

Grounding the neutral point by impedances causes a change in the fault current's magnitude and variation shape. The effects of grounding impedances have been shown in Figure 4. When the neutral point is grounded by a reactor, the magnitude of exponential fault current increases. Therefore the magnitude of fault current at fault occurrence moment is much more than the resistive grounded system. The maximum magnitude of fault currents for different grounding impedances is shown in Fig. 5.



(a)

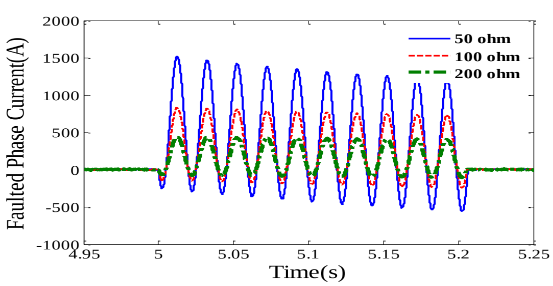


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Fig.4. Fault currents variations in a grounded neutral point – a): by resistor - b): by reactor

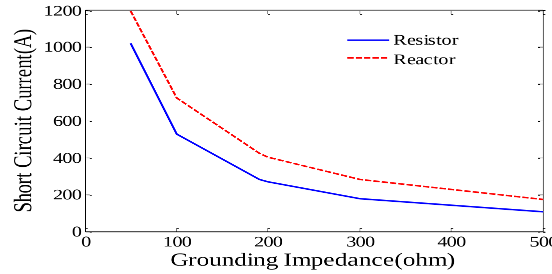
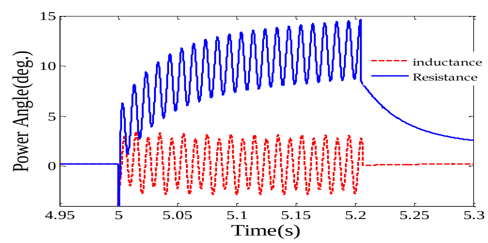


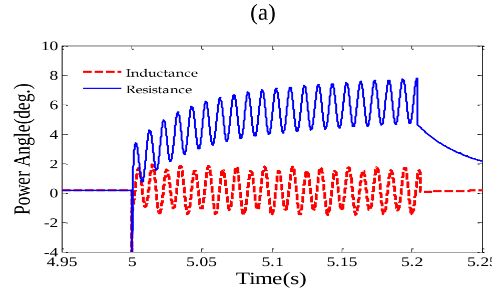
Fig.5. The maximum magnitude of fault currents vs NGR values

Using the resistor for the grounding system causes to decrease in the exponential term of the fault current. If the neutral point is grounded by a reactor, the behavior of the fault current is different for a while. In this case, the magnitude of the exponential term of current increases and causes to impose the higher currents.

One of the important parameters which have considerable variations during a fault is the power angle of the generator (δ). Fluctuations of power angle in L-G faults are very high and are dependent on the grounding impedance. Figure 6 shows the effect of values of grounding impedances on δ. Comparison with Figure 4. clears that although reactance grounding causes the higher amplitude of fault current but produces a very low magnitude of power angle variations. In other words, power angle with resistance grounding has an additive exponential component, while with a reactor, there is no dominant exponential term.



(a)

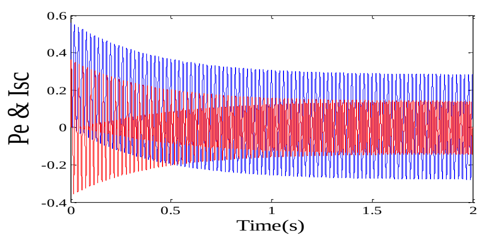


(a)

Fig.6. power angle variation during L-G fault –a): Zn=50Ω - b): Zn=100Ω

IV. DEFINITION OF A NEW GRAPHIC PATTERN FOR GROUND FAULTS

According to equation (4), the active power during the L-G fault is formed by 3 components: a DC offset, a descending sinusoidal component with power system frequency, and a steady-state sinusoidal component with twice the system's frequency. All of them are related to grounding impedance value and type via angle of θ. At the beginning of the fault, the exponential component is dominant in a solidly grounded system, and P_e varies with system frequency i.e. ω. But after a while, this component dissipates and P_e fluctuates with 2ω frequency. In an ungrounded or high resistance grounded system P_e swings with frequency 2ω during all the time of the fault. Figure 7 shows the per unit fault current and per unit power waveforms during the L-G fault. Figure 7-b shows the waveforms at the beginning of the fault. At this time the power and fault current have the same frequencies. But after a while, the frequency of fault power becomes twice of fault current as seen in Figure 7-c. For a high resistive grounded system because of the very low magnitude of exponential term, at whole fault duration, the frequency of power is 2ω.



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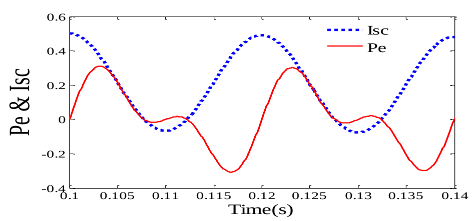

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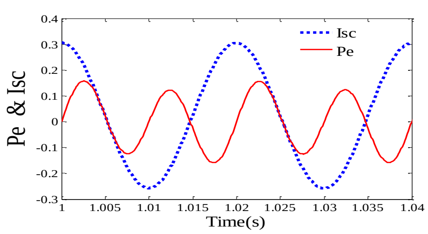
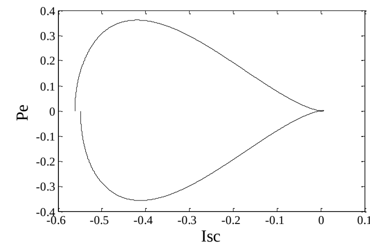


(c)

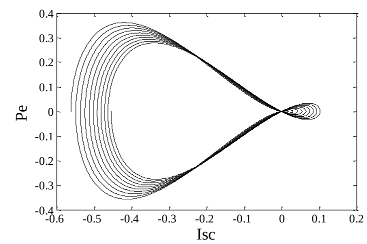
Fig.7. Power and current variations during L-G fault in a solidly grounded system. -a) the whole time of fault -b) start of fault -c) end of the fault

These differences can be used to define a special pattern for each fault. In this paper, a new graphic pattern for the fault, which is the locus of the power and current of the generator during the fault is introduced. The following will be shown that this locus is different for each type of fault. Figure 8 shows the locus of P_e vs I_{sc} in a solidly grounded system for L-G fault concerning the different times of fault. These loci reveal that while continuing the fault, the path repeats in similar shapes. For example, if the fault clearance time by the protection system is 0.2s and the rated frequency is 50Hz, it is expected to occur in ten circulations.

Moreover, by the time, the locus consists of two parts. A closed path on the right hand of the locus is also formed. This excrescence is created due to double the frequency of power.



(a) t =0.02s

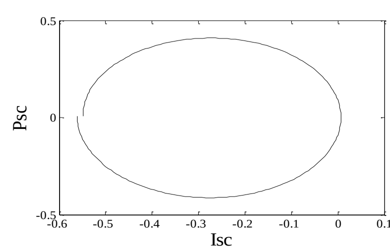


(b) t =0. 2s

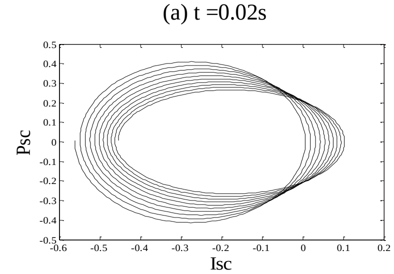
Fig.8. Locus of P_e vs I_{sc} in a solidly grounded system (as perunit values)

If the short circuit power swings with only the nominal frequency of system (like a 3 phase fault), locus has one section. Figure 9 shows the pattern of fault in a 3 phase fault with respect to different duration fault. The locus of this fault has been formed in one close part because the short circuit power consists of components with only the rated frequency of the system.

The value of grounding impedance and the phase of the voltage source can affect the shape of the locus. In all of the above locus, φ=0, and Z_n=0. To analyze the effect of grounding resistance value, the fault pattern is extracted for Z_n>0 and φ=0 as shown in Figure 10. The neutral point is grounded with resistance. The range of variations of fault current has been limited concerning previous conditions, as expected. Also, the locus moves towards symmetry as the resistance increases.

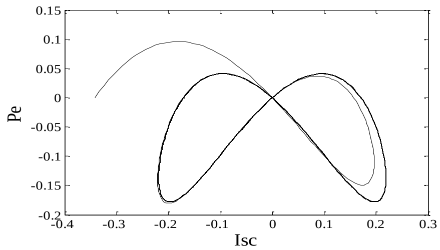


(a) t =0.02s

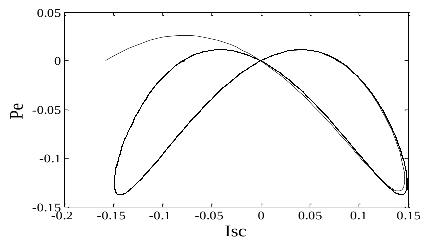


(b) t =0. 2s

Fig.9. Locus of 3phase fault power vs I_{sc}



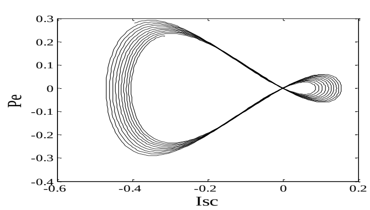
(a) Z_n =50$^{\Omega}$



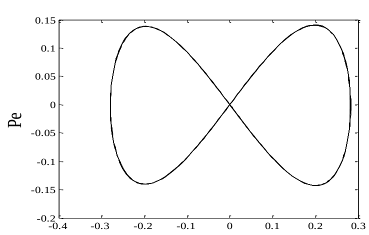
(b) Z_n =100 $^{\Omega}$

Fig.10. Locus of P_e vs I_{sc} with grounding resistance

Another important factor is the phase angle of the generator at fault occurrence moment. Figure 11 shows the locus for different values of φ while the neutral point has been grounded solidly. As φ increases the right-hand side of the locus grows. At φ=π/2rad both parts are identical and for φ=πrad the locus is the mirror of φ=0 (shown in Figure 8-b).
The entire above locus is extracted for the resistive grounded system. In the case of the neutral point grounded by a reactor, the fault pattern is very similar to a solidly grounded system. Figure 12 shows the locus of fault for different values of the reactor.



(a)



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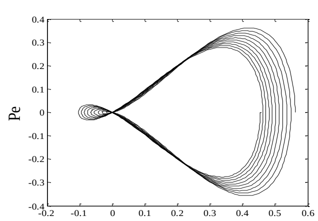
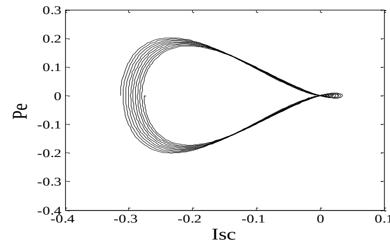
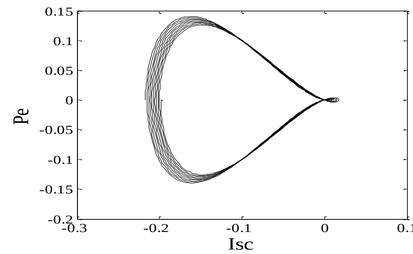


(c)

Fig.11. Locus of Pe vs Isc in a solidly grounded system a): φ =π/4 b): φ =π/2 c): φ =π



(a)



(b)

Fig.12. Locus of Pe vs Isc with grounding reactance (a):50Ω (b):100 Ω

V. CONCLUSION

In this paper, analytical expressions for L-G fault were derived. The effect of the grounding impedance characteristics, including type and value on power system parameters was studied using these equations. When the neutral point of the main transformer is grounded by a rector, the power system faces to higher magnitude of short circuit current. But the range of power angle variations is limiter than grounding resistance. In addition, a new pattern for ground faults defined and for different grounding conditions of the neutral point was analyzed.

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