Voltage Sag Mitigation by Neutral Grounding Resistance Application in Distribution System of Provincial Electricity Authority

S. Songsiri* and S. Sirisumrannukul

Abstract— *This paper presents an application of neutral grounding resistance (NGR) to voltage sag mitigation and the effects of different values of NGR on temporary overvoltage in a 22 kV distribution system of Provincial Electricity Authority (PEA). The overcurrent relays and the type K expulsion fuses are modeled using TACS (Transient Analysis and Control System) functions in Electromagnetic Transient Program (EMTP) to simulate voltage sags caused by ground faults and to calculate their voltage sag magnitude and duration. The magnitude of voltage sags are measured at the substation busbar and at the end of the faulty feeder via the delta/wye distribution transformer that represents the deepest voltage sags seen by end-user equipment. The effectiveness of neutral grounding resistance application are assessed in terms of extended fault clearing time, temporary overvoltage which affects surge arresters installed in the system. The study results indicate that appropriate values of NGR are able to effectively mitigate voltage sag while minimizing any other possible effects to the system. Appropriate neutral grounding resistances can help customers on other feeders connected at the same bus ride-though voltage sag events. Not only is the fault clearing time close to the solidly ground system reduced for this NGR, but the existing setting scheme for protection coordination is not necessary to be revised. In addition, no replacement costs for arresters and voltage transformers are introduced. It is also possible for the system to bypass the NGR to become a solidly grounded system whenever it fails.*

Keywords— **Voltage sag, Temporary overvoltage, Neutral grounding resistor, EMTP.**

1. INTRODUCTION

Voltage sag caused by faults or short circuits is one of the main power quality problems in overhead distribution systems. While an interruption of electric power supply affects only downstream customers, a voltage sag can create problems spread over the system. It was reported in [1] that even a voltage sag lasted only 4-5 cycles, it caused a wide range of sensitive customer equipment to drop out. Effects of voltage sag from faults or short circuits are characterized by its depth and duration which depend on current magnitude of the faults and clearing time of the associated protective devices. With reference to the ITIC curve shown in Figure 1 [2], sensitive equipment can function properly for a voltage sag magnitude of 0.8 per unit with a sag duration less than 10 seconds. To comply with this standard, many techniques have been proposed in literature for voltage sag improvement [3], such as reducing the number of faults, reducing of fault clearing time, changing or modifying power system design, using high immunity equipment or installing mitigation devices.

Since more than 70% of short circuits in overhead distribution systems are of single-line-to-ground fault, they are, therefore, the major cause of voltage sag problem and pose a serious threat to sensitive equipment.

The application of neutral grounding resistance offers an effective solution to limit current magnitudes of single-line-to-ground faults. This application is achieved by inserting a neutral grounding resistor (NGR) between the neutral point of power transformers and substation ground grids. An NGR of 12.7 ohms has been used in the Provincial Electricity Authority (PEA) system. However, this size of NGR would not be suitable to the system because the existing surge arresters fail to withstand temporary overvoltage (TOV) and hence they need to be replaced by ones with higher voltage rating.

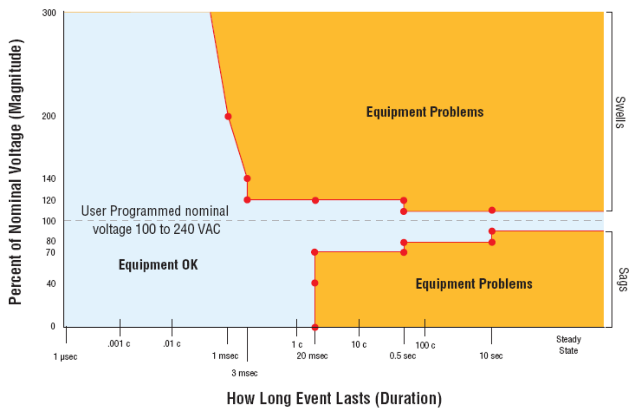

Fig.1. ITIC curve.

Effects of a voltage sag event from a fault or a short circuit generally depend upon the fault current magnitude and the clearing time of protective devices. These two factors determine the depth and duration of the voltage sag, respectively. With reference to the ITIC curve, sensitive equipment can still function properly for a voltage sag magnitude greater than 0.8 per unit with a

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sag duration less than 10 seconds. In general, the less ground fault current, the greater voltage sag magnitude.

This paper proposes an effective solution to mitigate the voltage sag problem caused by single-line to ground faults with four different neutral grounding resistances: 1) 0 ohm (solidly grounded), 2) 12.7 ohms, 3) 6.35 ohms and 4) 25.4 ohms. The main idea of the method is to reduce ground fault currents by inserting a neutral grounding resistor between the neutral point of the secondary winding of the power transformer and the ground at the substation as shown in Figure 2 so that the voltage drop in the source side of interesting nodes is reduced. The secondary side voltages of distribution transformers with vector group of Dyn11 are measured to evaluate the voltage sag mitigation. Low voltage sags at the secondary side of delta/wye distribution transformers directly affect end-user equipments. However, this type of winding connection is able to reduce the voltage sag magnitude of the phase-voltage on the secondary side because the magnitude transferred from the primary side is governed by the line-to-line voltage, not the phase voltage.

Another issue attached with the voltage sag problem is the temporary overvoltage (TOV) problem on the unfaulted phases during single line to ground faults. Temporary overvoltage may damage surge arresters installed at the 22 kV bus in the substation and the main feeder. The magnitude and duration of TOV with a number of fault locations will be investigated in this paper.

The methodology is simulated using TACS functions in EMTP to simulate the voltage sag events caused by faults or short circuits in a radial distribution system. The source impedance of the 115 kV bus supplied to each of the 22 kV systems is obtained from a study report of PEA short-circuit level and their power transformer impedance is taken from standard parameters.

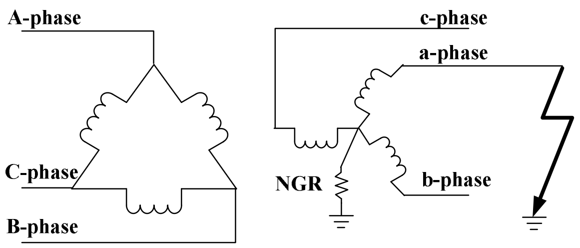


Fig. 2. Installation of neutral grounding resistor.

2. MODELLING OF PROTECTIVE DEVICES

TACS functions in EMTP are used to model circuit breakers and expulsion fuses, which are the common devices in PEA's overhead distribution systems.

Expulsion Fuses

The operating time of expulsion fuses consists of melting time and arcing time [5]. The melting time depends on melting energy. The model of expulsion fuses are made up with two parts: 1) melting model and 2) arcing model. Figure 3 illustrates a diagram that shows the two parts of the expulsion fuse model. Fortran statements and devices in TACS used to model the melting part are Multiplier, Integrator, Comparator and General. The melting energy is calculated from the clearing time-current curve, instead of the melting time-current curve. The reason is that for the same fault current, the former curve gives a longer clearing time and therefore longer voltage sag duration. The value of melting energy is calculated from the average value of I^2t for the current, I , in the range from 5 times as much as expulsion fuse's rated current up to the maximum current in its time-current curve. The arcing part is modeled by a TACS switch which will open after receiving two command signals: one for opening (point A of Figure 4) and the other for first detected zero-crossing (point B of Figure 4). Note that point A is determined from the intersection between a simulated value of I^2t and the melting energy. In other words, at point A the fuse element starts to blow.

Circuit Breakers

A circuit breaker is a mechanical switch capable of interrupting fault current and reclosing the circuit. The circuit breaker is operated by the command of the involved relay. The operating time for the opening of the circuit breaker is the combination of relay operating time and circuit breaker breaking time. The circuit breaker model in this paper does not include dynamic arc and possibility to failure of all opening operations [6].

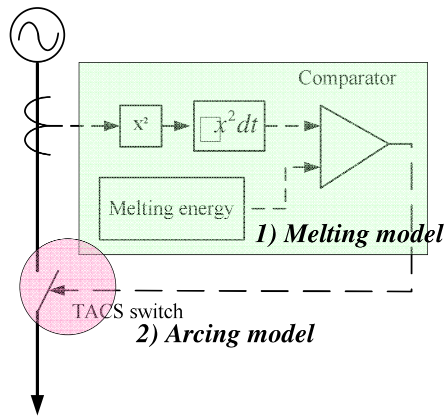


Fig.3. Diagram of expulsion fuse model.

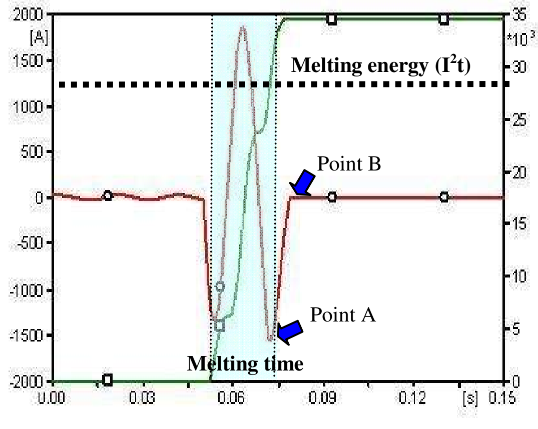


Fig.4. Operating time of expulsion fuse.

The most commonly seen over current relay functions are instantaneous and time delay. The operating time of time delay function is related with the inverse time-current curve, time-current characteristics of which are classified by the IEC standard as inverse, very-inverse and extremely-inverse curves.

The very-inverse and extremely-inverse curves are currently implemented in PEA's distribution systems. The current and time relationship is mathematically expressed by equation (1).

The circuit breaker operation model can be divided into two parts: 1) protective relay model and 2) circuit breaker model, as shown in Figure 5. A protective relay model is created with TACS to detect current values via a current transformer (divider). The measured current values are then sent to calculate the tripping time and the pick-up time based on an associated current-time characteristic formula. A trip signal will be made at the time at which the reference time reaches a set point.

$$t(I) = \frac{K}{\left(\frac{I}{I_p}\right)^n - 1} \times TMS \tag{1}$$

where $t(I)$ = interruption time

I = short-circuit current

I_s = pickup current

TMS = time multiplier

K = family factor

n = characteristic type factor

Typical values of K and n are shown in Table 1 for inverse, very inverse and extremely inverse current-time characteristics.

Table 1. Coefficient factors of current-time characteristics

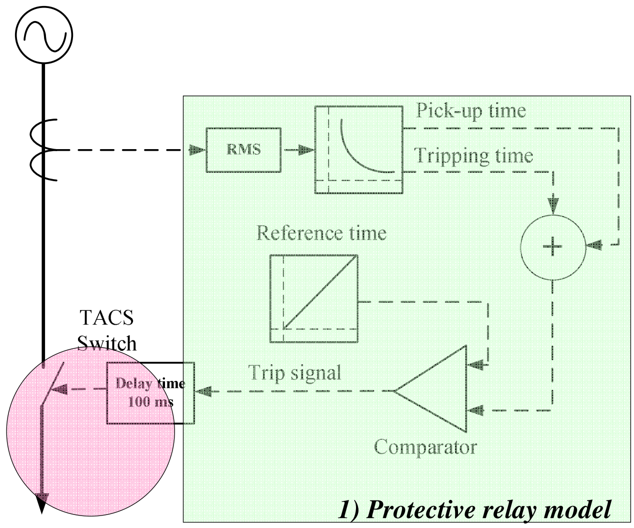
Current-time characteristic	K	n
Inverse	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2

Due to mechanism parts and contact traveling of circuit breaker, time delay is considered as the opening time of circuit breaker model. The opening time of bulk-oil circuit breakers and modern vacuum circuit breakers is 250 ms and 50 ms, respectively [7]. In PEA's distribution systems, all circuit breakers are of vacuum type with opening time ranging between 60 and 70 ms obtained from test reports. These opening times may not be suitable in the circuit breaker model owning to errors, for example, from current transformers, time delay from auxiliary contacts. Hence, an opening time of 100 ms is selected to account for such an error. Another TACS switch is used to represent the arcing time of the circuit breaker.

3. TEMPORARY OVERVOLTAGE

A ground fault introduces temporary overvoltage (TOV) on the unfaulted phases with duration of fault clearing time. The grounding system determines the magnitude of this voltage. The maximum temporary overvoltage is $\sqrt{3}$ times the nominal line-to-ground voltage for the ungrounded system. The impedance grounded system (including resistance grounded system) gives a higher temporary overvoltage than solidly grounded system as shown in Figure 6.

For the solidly grounded system, grounding resistor R_g is usually very small. For this reason, the voltage between the neutral and the ground (V_{gn}) is also small or almost zero, leaving temporary overvoltage on the unfaulted phases equal to the phase-voltage.



2) Circuit breaker model

Fig.5. Circuit Breaker Operation Model

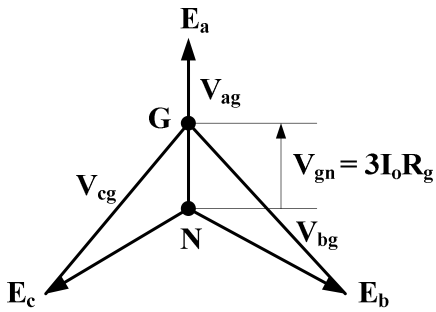


Fig. 6. Temporary overvoltage on b-phase and c-phase during a single-line to ground fault at a-phase.

TOV occurs between the phase and ground and affects electrical equipment installed between the phase and ground. The arrestor, as an example, has the capability to withstand TOV defined by the manufacture in terms of TOV in per unit value of the arrester's MCOV. TOV increases current, power dissipation and temperature in metal-oxide arresters. These negative conditions affect the protection and survivability characteristics of the arresters. The TOV capability of the arresters must meet or exceed the expected temporary overvoltages of the system. The TOV capability was tested and made by manufacturer, as an example shown in Table 2 [8]. The prior-duty TOV capability can be used to evaluate arresters installed in the distribution system. The arresters mounted at the substation and in the feeder are, respectively, the station class and normal heavy duty distribution class.

PEA uses arresters with a rated voltage (U_r) of 21 kV with a maximum continuous operating voltage (MCOV) of 17 kV for the solidly grounded system and U_r of 24 kV with MCOV of 19 kV for the resistance grounded system.

Table 2. TOV capability of MOV surge arresters

TOV duration (seconds)	TOV capability (p.u. of MCOV)			
	Normal heavy duty	Riser pole	Intermediate	Station
0.02	1.73	1.56	1.56	1.56
0.1	1.62	1.49	1.49	1.50
1	1.55	1.41	1.41	1.42
10	1.47	1.35	1.35	1.36
100	1.40	1.31	1.31	1.32
1000	1.33	1.28	1.28	1.28

4. COEFFICIENT OF GROUNDING AND EARTH FAULT FACTOR

The coefficient of grounding (COG) [8] is defined as the percentage of the highest r.m.s. value of a line-to-ground voltage on the unfaulted phases and the r.m.s value of the line-to-line voltage when the fault is removed as defined in equation (2). Multiplying COG by a factor of $\sqrt{3}$ defines the earth-fault factor (EFF) given in equation (3) [8].

$$COG = \frac{E_{LG}}{E_{LL}} \times 100\% \qquad (2)$$

$$EFF = \sqrt{3}\frac{COG}{100} \qquad (3)$$

where COG = coefficient of grounding
E_{LG} = line-to-ground voltage of the unfaulted phases
E_{LL} = line-to-line voltage when the fault is removed
EFF = earth fault factor

5. CASE STUDY

This section presents simulation results of a 22 kV distribution system in PEA with a high source impedance based on its short-circuit level of equivalent driving point at the 115 kV bus. The system is located at Dansai in Loey Province and considered as a weak source system. This existing solidly grounded system is served as the base case for comparative studies. The r.m.s. voltage measurements are detected via a delta/wye distribution transformers at the 22 kV bus and at the end of the faulted feeder to evaluate voltage sag.

The GOC, EFF and TOV capability of arresters are evaluated at fault locations. The TOV capability of arresters having different MCOV is analyzed with the 4 configurations of different system grounding. Since TOV duration depends on fault clearing time due to the operation of protective devices, its capability can be improved by reducing fault clearing time, for example, by relay setting or fuse sizing.

Test System

Figure 7 shows a single line diagram of the test system. The system has one feeder connected to a power transformer at the 22-kV bus via a circuit breaker.

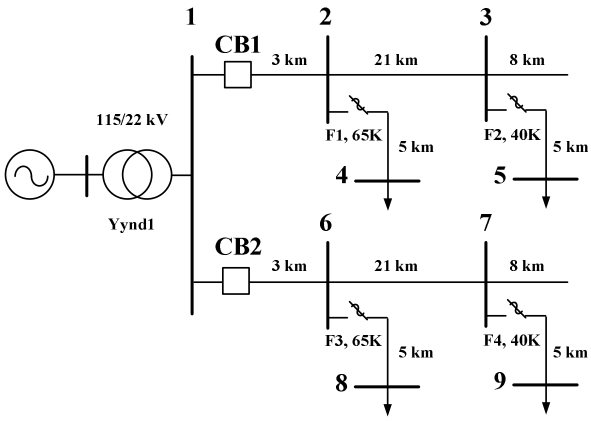


Fig.7. Single-line diagram of test system.

The system parameters of the test system are provided in Table 3, with system base of 100 MVA, 115 kV/22 kV.

Table 3. System parameters of test system

Parameters	Dansai Substation
115 kV source	Z_1=0.056+j0.294 pu Z_0=0.064+j0.369 pu
Power transformer	YNyn0d1 $\%Z_{HV-LV}$ = 7.5% $\%Z_{HV-TV}$ = 4.5% $\%Z_{LV-TV}$ = 4.5%
Feeder Line	Z_1=Z_2=0.214+j0.224 Ω /km Z_0=0.460+j1.755 Ω /km
Branch circuit	Z_1=Z_2=764+j0.318 Ω /km Z_0=1.002+j1.693 Ω /km

Protection Coordination

Assume that the fault impedance of all fault events is zero. Protection coordination is intended to meet the following requirements.

- The circuit breaker will operate for any short-circuits on the main feeder.
- The fuses will operate faster than the circuit breaker for any faults downstream from them.

PEA's setting criteria of overcurrent relay for feeder protection are of extremely inverse time delay characteristics. Table 4 shows the relay setting parameters used in the base case.

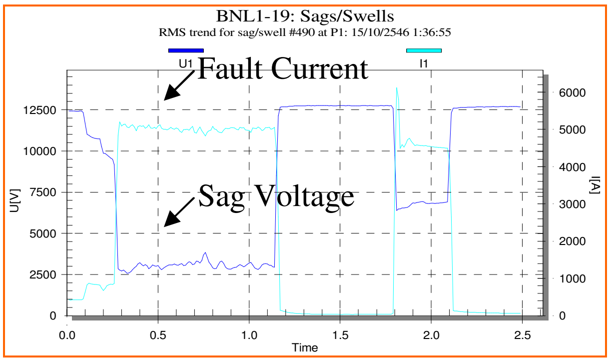
Table 4. Overcurrent relay setting parameters

Protection type	Characteristic curve	Pick-up current (A)	Time multiplier
Phase	Extremely inverse	420	0.125
Ground	Extremely inverse	105	1.000

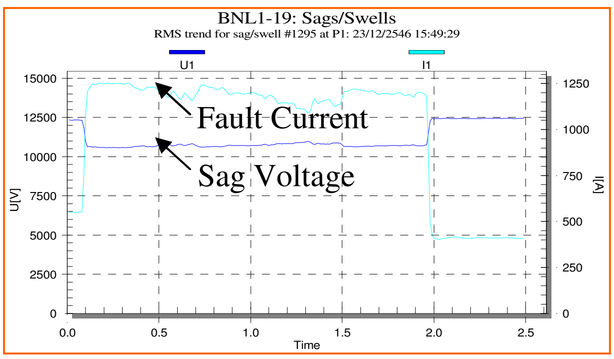
Mitigation technique

As shown in Figure 6, if the grounding resistor (R_g) is increased by inserting the Neutral Grounding Resistor (NGR) between the neutral (star) point (at secondary side of power transformer) and ground grid then the voltage between neutral and ground (V_{gn}) is raised up. The increasing of V_{gn} can mitigate the voltage sag problem on the medium voltage level. Consequently, the NGR can mitigate voltage sag problem and much more resistance gives the better result for voltage sag mitigation but the TOV is also high. The optimum value of NGR should be selected to install.

The improvement when using the NGR of 12.7 ohms in PEA's distribution system was evaluated by recording the voltage and current at substation bus during the single-line-to-ground fault occurred. The voltage sag after NGR installed was improved from 0.23 p.u. to be 0.81 p.u. as shown in Figure 8.



(a)



(b)

Fig. 8. Voltage sag improvement (a) before (b) after installation of resistance grounded system (12.7 ohms).

Voltage sag magnitude and duration

As already described, a voltage sag magnitude of 0.80 p.u. is used as the upper bound for equipment survivability due to single-line-to-ground faults with different grounding resistances. The voltage sag magnitude and duration are measured as phase-voltage at the secondary side of the delta/wye distribution transformers installed at the 22 kV bus in the substation and at every 5 km downstream from the substation. To be specific, there are in total 5 different fault locations. Figures 9, 10, 11 and 12 show simulation results of the corresponding 5 fault locations (or 5 voltage sag events) superimposed on the ITIC curve for the 4 cases of grounded resistance, respectively.

As shown in Figure 9, some of the sag events occur near the substation can suffer from voltage sag problems to customers' equipment. When the fault location moves away from the substation, the voltage magnitude is improved.

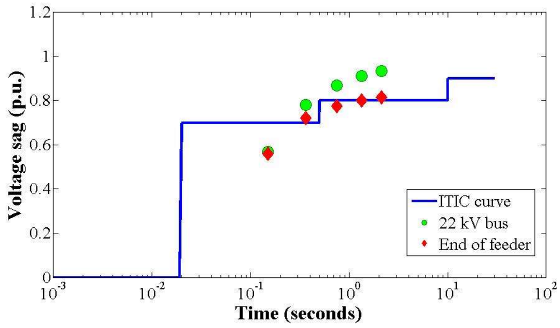


Fig. 9. Voltage sag magnitude and duration in solidly grounded system.

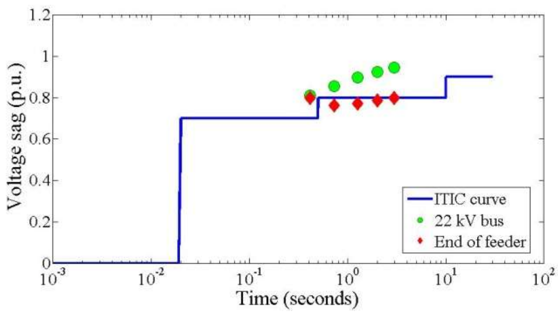


Fig. 10. Voltage sag magnitude and duration in resistance grounded system (6.35 ohms).

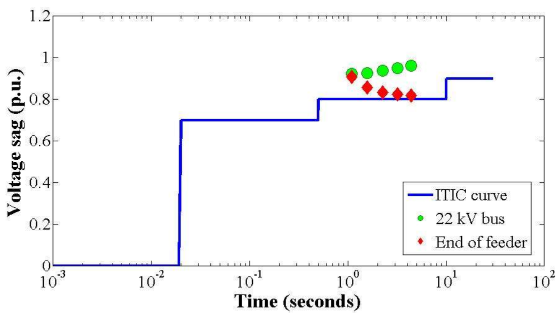


Fig. 11. Voltage sag magnitude and duration in resistance grounded system (12.7 ohms).

In Figure 10, the voltage sags at the secondary side of the distribution transformer installed at the substation bus do not pose any for all the locations. Although the customers at the far-end point of the faulted feeder remain in trouble, trying to raise the voltage magnitude is of no use because the faulted feeder will be later isolated, causing interruption to all the load points connected it. We can see that the voltage sag durations are slightly longer than the solidly grounded system.

Figures 11 and 12 demonstrate that the voltage sags at the secondary side of distribution transformer installed at both locations are improved even at the far-end point in the faulted feeder. The voltage sag durations are longer than the solidly grounded and 6.35-ohm grounded system. Especially for the 25.4-ohm grounded system, the fault clearing times are too long; the protection coordination should be concerned. When faults move away from substation, the voltage sags at substation bus are improved but the voltage sags at far-end point are worst.

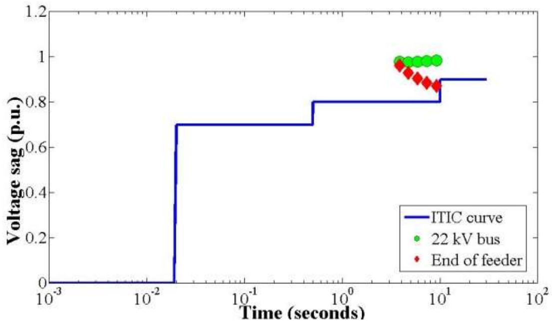


Fig. 12. Voltage sag magnitude and duration in resistance grounded system (25.4 ohms).

COG and EFF

The system with different grounding resistances gives different COG and EFF. The COG and EFF are calculated and shown in Tables 5 and 6.

Table 5. COG of Different Grounded Systems

System Grounding	Coefficient of Grounding (%)				
	Bus	5 km	10 km	15 km	20 km
Solidly	54.70	70.12	75.31	77.47	78.48
6.35-ohm	100.36	89.41	84.11	81.39	79.78
12.7-ohm	101.68	95.77	91.24	87.96	85.59
25.4-ohm	100.99	98.41	95.93	93.63	91.59

Table 6. EFF of The Different Grounded Systems

System Grounding	Earth Fault Factor (p.u.) at different fault location				
	Bus	5 km	10 km	15 km	20 km
Solidly	0.95	1.21	1.30	1.34	1.36
6.35-ohm	1.74	1.55	1.46	1.41	1.38
12.7-ohm	1.76	1.66	1.58	1.52	1.48
25.4-ohm	1.75	1.70	1.66	1.62	1.59

Tables 5 and 6 reveal that the system with a higher value of NGR creates a higher COG and EFF. When a ground fault occurs, the voltage between the unfaulted phases and the ground in a high COG and EFF system system will be raised higher than in a low COG and EFF system. Therefore, the TOV across the arresters installed on the unfaulted phases can be expected high.

Temporary Overvoltage

TOV performance is evaluated by measuring the voltage between the unfaulted phases and the ground. That TOV are divided by MCOV of existing arresters (21 kV rated voltage with 17 kV MCOV) and have same duration of voltage sag at the same fault location. The calculated TOVs in per unit are compared with the TOV capability given by the manufacturer [9]. The TOV occurred at different fault locations are compared with the arrester's TOV capability as shown in Figure 13 to Figure 16.

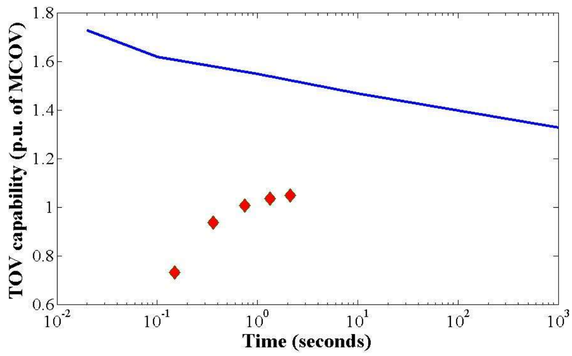


Fig.13. TOV at fault location and 21 kv arrester's tov capability in solidly grounded system.

Figure 13 shows that the TOVs generated by all fault locations are below the TOV capability of the 21 kV arresters. Therefore, the arresters can still operate properly without the risk of damage. The TOV tends to increase by distance away from the substation for the solidly grounded system while, the resistance grounded system, in contrast as shown in Figures 14-17, is likely to be high when the fault is near the substation. The reason is that when there is a single-line-to-ground fault of A-phase at the substation in the NGR system (refer to Figure 6), almost 100% of the phase voltage drops at R_g, giving V_{gn} very close to E_a. The voltage between the unfaualted phases and the ground (i.e., V_{bg} and V_{cg}) are almost equal to the phase-phase voltage. If the fault location moves away from the substation, the line impedance increases and lowers the fault current and V_{gn}. The resulting voltage between the unfaulted phases to the ground therefore decreases.

For a given grounded resistance, if the maximum TOV gets closer to the TOV capability curve, the arresters will be under more stress and should be replaced by a higher rating. The arresters with 24 kV rated voltage and 19 kV MCOV would be selected to install instead of the existing one.

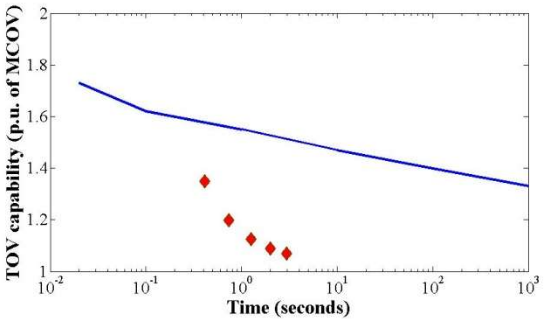


Fig.14. TOV at fault location and 21 kV arrester's TOV capability in 6.35-ohm resistance grounded system.

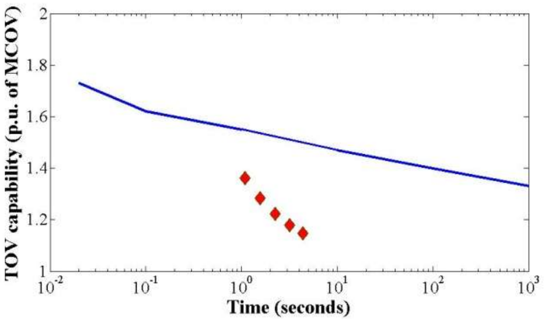


Fig.15. TOV at fault location and 21 kV arrester's TOV capability in 12.7-ohm resistance grounded system.

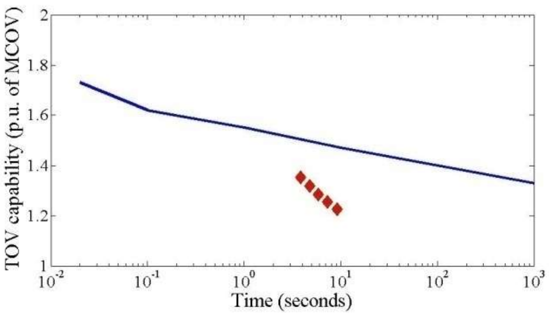


Fig.16. TOV at fault location and 21 kv arrester's TOV capability in 25.4-ohm resistance grounded system.

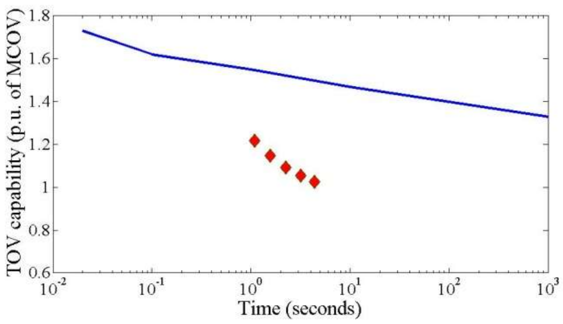


Fig.17. TOV at fault location and 24 kv arrester's TOV capability in 12.7-ohm resistance grounded system.

Figure 17 shows the TOV for the 12.7-ohms resistance grounded system with the replacement of a 24 kV rated voltage arresters. It can be seen that the arresters are now safer to install and operate in the system.

6. CONCLUSION

A method of neutral grounding resistor to ease voltage sag related problem in PEA's distribution system has been presented in this paper. A 12.7-ohm neutral grounding resistor was installed between the neutral point of the power transformer and the ground grid in the substation. The appropriate neutral grounding resistance (NGR) can be obtained for any three-phase/three-wire distribution system with very low unbalance current which can damage the NGR by overheating and the power transformer' secondary side has to be star or wye connection for NGR installed between neutral point and ground. However, this amount of resistance would not be appropriate to the system because the voltage rating of the arresters may need upgrading from 21 kV to 24 kV to avoid possible damage and therefore introduce investment cost and reconstruction work. The results of the case study suggests that halving the existing 12.7-ohm NGR (i.e., 6.35 ohms) would be a good alternative as it not only helps reduce the fault clearing time close to the solidly grounded system, but also no arrester and voltage transformer replacement costs are associated. In addition, the existing protection coordination setting does not need to be revised. Most importantly, if a NGR fails, the system can return to solidly grounded system by bypassing the damage the NGR. However, NGR can solve only voltage sag problems due to single-line-to-ground faults. The customers connected to the faulted feeder are still disconnected and do not obtain any benefit from NGR application. In such a case, other techniques should be employed, for example, reducing the number of faults, using uninterruptible power supply or applying ground fault current neutralizer (Peterson's coil).

REFERENCES

[1] Lamoree, J., Mueller, D., Vinett, P., Jones, W., and Samotyj, M.. 1994. Voltage Sag Analysis Case Studies. *IEEE Trans. Industry Applications*, 30(4) 1083-1089.

[2] Martinez, J.A. and Martin-Arnedo, J. 2006. Voltage Sag Studies in Distribution Network-Part II: Voltage Sag Assessment. *IEEE Trans. Power Delivery,* 21(3) 1679-1688.

[3] Sannino, A., Miller, M.G., and Bollen, M.H.J.. 2000. Overview of Voltage Sag Mitigation. *IEEE Power Engineering Society Winter Meeting,* 4: 2872-2878, January.

[4] Zeng, X., Li K.K., Chan W.L., and Yin X. 2004. Some Novel Techniques for Improving Power Quality in Distribution Networks. *EEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, 1: 306-310, April.

[5] Tanaka, T. and Yamasaki, M. 2004. Modeling of Fuses for Melting Time and Fusing Current Analysis. *IEEE Telecommunications Energy Conference*, 671-675, September.

[6] Martinez, J.A. and Martin-Arnedo, J. 2004. Modeling of Protective Devices for Voltage Sag Studies in Distribution Systems. *IEEE Power*

Engineering Society General Meeting, 1: 451-456, June.

[7] Hindle, P.J. and Sanderson, J.V.H. 1997. Overcurrent Protection Co-ordination: a Modern Approach for Modern Devices. *IEEE Development in Power System Protection, Sixth International Conference,* 62-65, March.

[8] IEEE Standard C62.92-2000. 2000. IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems. USA, September.

[9] Hernandez, J. Lightning Arrester: A Guide to Selection and Application. *General Electric Company*.