# Voltage Sag Mitigation by Revised Protection Coordination Scheme in Distribution System of Provincial Electricity Authority

S. Songsiri and S. Sirisumrannukul

***Abstract***— *This paper proposes a revised protection coordination scheme for voltage sag mitigation in 22-kV distribution systems 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 faults or short circuits in radial distribution systems. For a given voltage sag magnitude of interest, voltage sags caused by a single-line to ground fault and a three-phase fault are simulated to calculate two parameters: the critical distance (equivalently to bus voltage magnitude) measured from the substation downstream to the feeder and the associated fault clearing time. These two parameters are projected on the Information Technology Institute Council (ITIC) curve. If voltage sag events stay outside the immunity region of the ITIC curve, the fault clearing time will be reduced by adjusting the protective relay's characteristic and/or resizing the fuse rating while complying with the criteria of fuse blowing scheme established in PEA. The proposed methodology is simulated on EMTP and tested with 22-kV Dansai and Thammasat University distribution systems. The results indicate that the revised proposed scheme of protection coordination can help customers on other feeders connected at the same bus ride-though voltage sag events that occur beyond the critical distance of the faulted feeder and therefore provide a practical, cost-effective way for voltage sag mitigation.*

***Keywords***— **Voltage sag, protection coordination, EMTP, distribution system.**

## 1. INTRODUCTION

Voltage sag is one of the main power quality problems in overhead distribution systems, which are exposed to faults or short circuits. Faults or short circuits can cause either interruptions or voltage sags. An interruption of electric power supply affects only downstream customers but voltage sags can create problems spread over the system. Even a voltage sag lasting only 4-5 cycles can cause a wide range of sensitive customer equipment to drop out [1].

The effects of voltage sag from fault or short circuit generally depend on fault current magnitude and clearing time of protective device. These two factors determine the depth and duration of voltage sag, respectively. With reference to the ITIC curve as shown in Figure 1 [2], sensitive equipment can function properly for a voltage sag event with a sag duration less than 20 milliseconds, for a sag magnitude of 0.70 per unit with duration less than 0.50 second, or for a sag magnitude of 0.80 per unit with a sag duration less than 10 seconds.

There are many techniques for voltage sag improvement [3] such as reducing the number of faults, reducing of fault clearing time, changing power system design, using high immunity equipment or installing mitigation devices. Of these alternatives, reducing of fault clearing time without changing equipment by revising protective coordination scheme or changing fuse rating is cost-effective and hence the most attractive.

This paper proposes a revised protection coordination scheme for voltage sag mitigation. The main idea is to reduce the fault clearing time of the circuit breaker and/or to resize the rating of expulsion fuse closet to the substation while satisfying the criteria of fuse blowing scheme established in PEA. The methodology is simulated using TACS functions in EMTP to simulate the voltage sag caused by faults or short circuit in a radial distribution system. Two 22 kV distribution systems in PEA are tested with 2 different source impedances, namely high and low impedances. 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 impedances are taken from standard parameters.

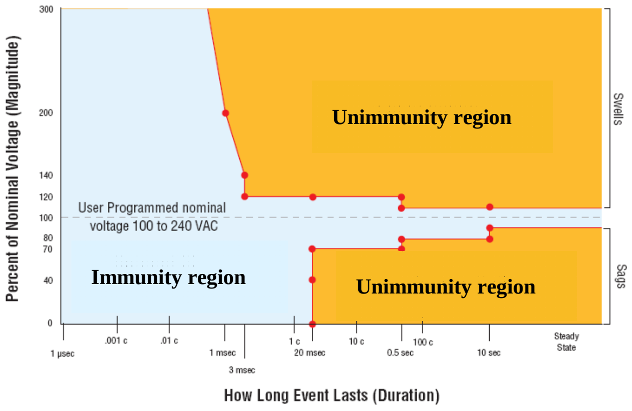

**Fig.1. ITIC Curve**

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The critical distance of faults in feeder [4] that causes voltage sag to stay outside the immunity region of the ITIC curve will be identified. Different protection schemes are investigated to evaluate the performance of voltage sag mitigation on the test system. The simulation results indicate that factors that affect voltage sags are fault locations, fuse sizing, overcurrent relay settings, and source impedance. In addition, by revising the existing protection coordination scheme, voltage sag problems can be effectively mitigated.

## 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 overhead distribution system.

### *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 2 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 3) and the other for first detected zero-crossing (point B of Figure 3). 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.

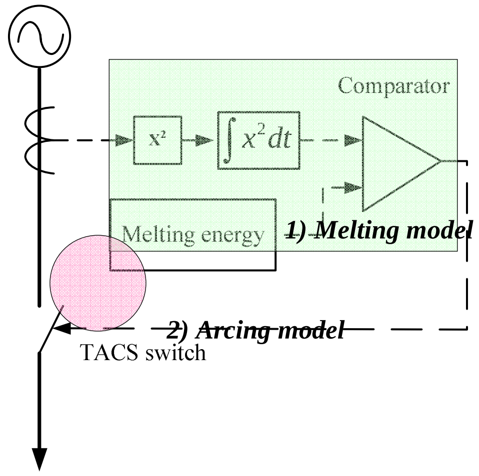


**Fig.2. Expulsion fuses model diagram**

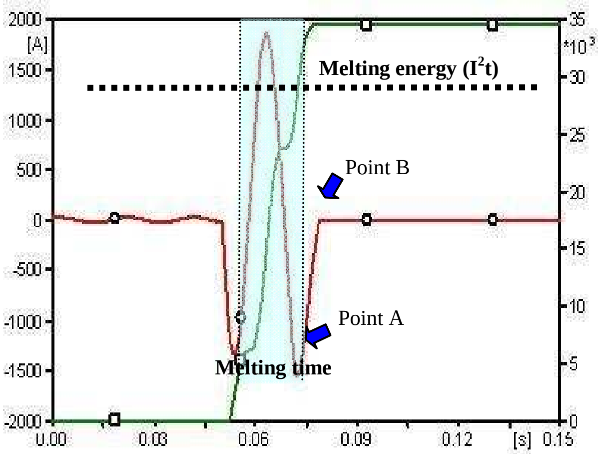
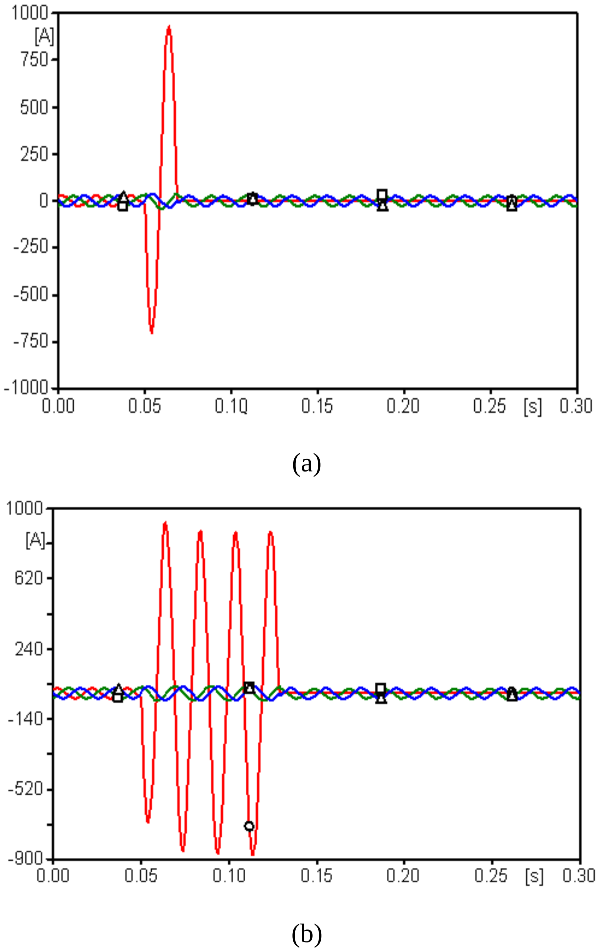


**Fig.3. Operating Time of Expulsion Fuses**



(a)

(b)

**Fig.4. Operating Time of Different Rated Current Fuse on Same Short-circuit Current: (a) Type 10K and (b) Type 25K**

As shown in Figure 4, different rated current expulsion type K fuses are simulated at same location. We see that a lower rated current gives a shorter operating time; for example, the 10K fuse takes about 1 cycle for blowing while the 25K one takes about 4 cycles.

### *Circuit Breakers*

A circuit breaker is a mechanical switch capable of interrupting fault current and reclosing a circuit. The circuit breaker is operated by the command of the involved relay. The operating time for opening of 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].

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 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

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

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 Characteristic**

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

Figure 5 shows very inverse and extremely inverse current-time characteristics. The circuit breaker operation model can be divided into two parts: 1) protective relay model and 2) circuit breaker model, as shown in Figure 6. 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 setpoint.

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 breaker and modern vacuum circuit breaker is 250 ms and 50 ms respectively [7]. In PEA's distribution systems, all circuit breakers are of vacuum type with opening times 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.

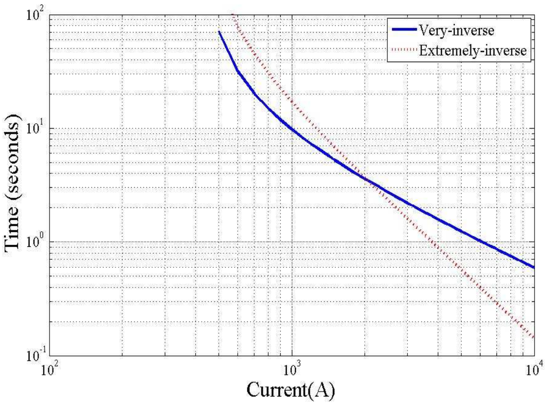


**Fig.5. Current-time Characteristic Curves**

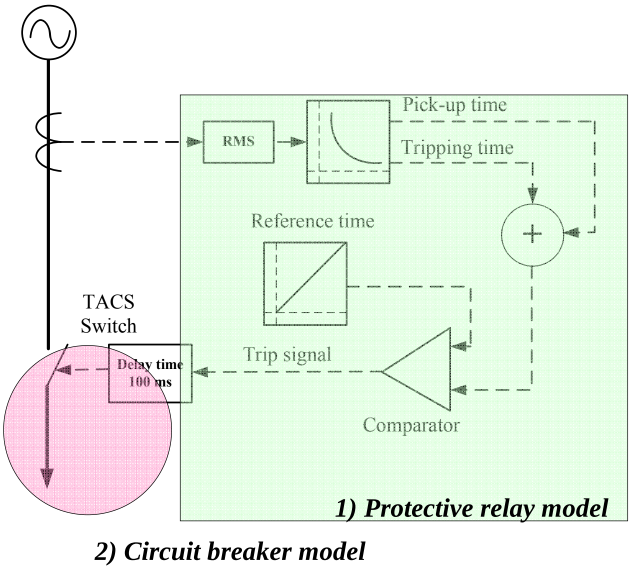


**Fig.6. Circuit Breaker Operation Model**

## 3. CRITICAL DISTANCE

Voltage sag magnitude is a function of the distance of fault from the substation. To be specific, shorter distance gives deeper voltage sag. The voltage divider model shown in Figure 7 can create an equation of voltage magnitude at the substation bus ($V_{sag}$) as a function of pre-fault voltage ($E$), source impedance ($Z_S$) and impedance between the substation bus and fault location ($Z_F$).

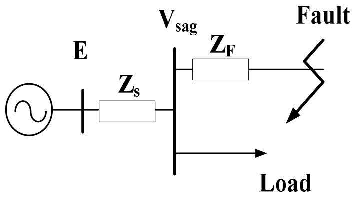


**Fig.7. Voltage Divider Model for Voltage Sag**

Eqn. (2) is expressed for voltage sag calculation as described above.

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \qquad (2)$$

The above equation indicates that a fault location closer to the substation bus produces less voltage sag magnitude (i.e., deeper sag). According to [8], the critical distance is defined as the distance to fault which leads to a sag of certain magnitude and causes a problem to equipment trip. The critical distance varies depending on the strength of source (source impedance) and the feeder impedance. The critical distance of a strong source system is shorter than that of a weak one. In this paper, a voltage sag magnitude of 0.70 p.u. is served as the benchmark for calculation of the critical distance. This magnitude is of interest because referring to the ITIC curve, the clearing time of the circuit breaker may not be fast enough to avoid voltage sag problems for that magnitude.

## 4. FAULT CLEARING TIME

The sag duration of a voltage sag event caused by a short circuit or a fault is much influenced by the fault clearing time of the protective devices. In general, fault clearing times in transmission system are shorter than in distribution system. A fault clearing time of various protective devices is given as follows [8].

- current-limiting fuse: less than one cycle
- expulsion fuse: 10-1,000 ms
- distance relay with fast circuit breaker: 50-100 ms
- distance relay in zone 1: 100-200 ms
- distance relay in zone 2: 200-500 ms
- differential relay: 100-300 ms
- overcurrent relay: 200-2,000 ms

With reference to the ITIC curve in Figure 1, a voltage sag magnitude of 0.70 p.u. with duration less than 0.50 second will not cause equipment to trip. As clearing time mentioned above, it can be seen that an overcurrent relay for feeder protection can avoid equipment tripping by reducing its fault clearing time.

## 5. SIMULATION PROCEDURE

In the simulation procedure, only single-line-to-ground and three-phase faults within the distribution network are of interest. The simulation procedure can be summarized as follows.

Step 1: Simulate the system with strong and weak sources to see the differences of voltage sag performance.

Step 2: Create single-line-to-ground and three-phase faults at every 1 km, starting from the substation bus downstream to the end of feeder. The magnitude of voltages at substation bus during faults and fault clearing times are measured for each fault event.

Step 3: Determine the critical distances that give a voltage sag of only 0.70 p.u. Any sag events with voltage sag magnitudes between 0.70 p.u. and 0.80 p.u. are evaluated with the ITIC curve because of inverse time-current characteristic of overcurrent relay. For sag events with magnitude greater than or equal to 0.80 p.u., they will not be considered as they are in the immunity region.

Step 4: If the sag events stay outside the immunity region, the overcurrent relay will be adjusted to reduce its operating time so that the events can be shifted into the sag problem-free zone. Protection coordination of the circuit breaker and the expulsion fuse closet to the busbar will be checked whether such an adjustment satisfies the fuse blowing scheme. If it does not, reduce the rating of the fuse or further adjust the time multiplier of the relay.

## 6. CASE STUDY

This section presents simulation results of two 22-kV distribution systems in PEA with 2 different source impedances (high and low impedances) based on the short-circuit level of equivalent driving point at 115 kV bus. The first system is located at Dansai in Loey Province and considered as a weak source system. The second system is located at Thammasat University in Pathumthani Province and considered as a strong source system. The existing scheme of PEA is served as the base case for comparative studies. The RMS voltage measurements are detected at 22 kV bus to evaluate critical distance, depth of sag and fault clearing time.

### *Test System*

Figure 8 shows the single line diagram of the test system. The system has one feeder connected to a power transformer at 22-kV bus via a circuit breaker. The feeder circuit supplies one branch circuit at the beginning and another branch circuit at the end. Both laterals are protected by expulsion fuses (type K) connected at tapping point of the branch circuits.

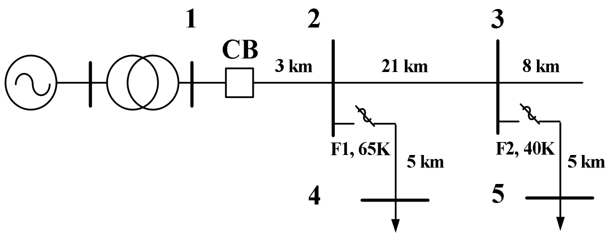


**Fig.8. Single-line Diagram of Test System**

The system parameters of test systems are provided in Table 2. System base is 100 MVA, 115kV/22kV.

**Table 2. System Parameters of Test System**

| Parameters | Substation | |
|---|---|---|
| | Dansai | Thammasat University |
| 115 kV source | $Z_1$=0.056+j0.294 pu | $Z_1$=0.006+j0.058 pu |
| | $Z_0$=0.064+j0.369 pu | $Z_0$=0.032+j0.206 pu |
| Power transformer | YNyn0d1 | Dyn1 |
| | $\%Z_{HV-LV}$ = 7.5% | %Z=12% |
| | $\%Z_{HV-TV}$ = 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 concepts.

- 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 3 shows the relay setting parameters used in the base case.

**Table 3. 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 |

### *Critical Distance*

As already described, a voltage sag magnitude of 0.70 p.u. is used to calculate the critical distance at Dansai substation and Thammasat University substation for both single-line to ground fault and three-phase fault. As shown in Figure 9, the critical distances of Dansai substation are 7.5 km and 20 km for single-line to ground fault and three-phase fault respectively. The critical distances of Thammasat University substation are 3.8 km for single-line to ground fault and 8.8 km for three-phase fault, illustrated in Figure 10.

Referring to Eqn. (2) and simulation results of critical distances in Figures 9 and 10, it is confirmed that the critical distances of the strong source are shorter than of the weak source. Therefore, a shorter critical distance is less likely to suffer from voltage sag due to a smaller area required to be protected from fault events caused by voltage sags with magnitudes deeper than 0.70 p.u.

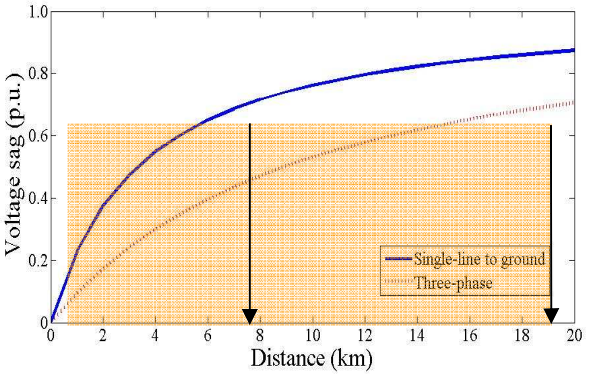


**Fig.9. Critical Distances of Dansai Substation**

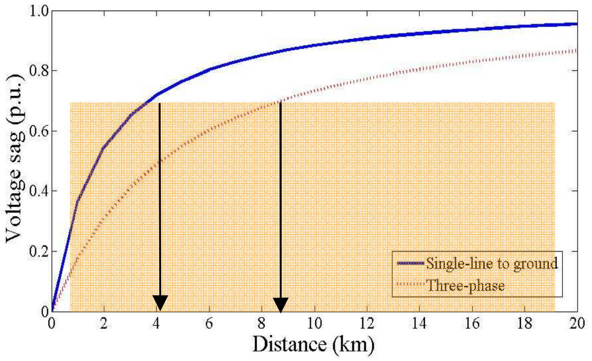


**Fig.10. Critical Distances of Thammasat University Substation**

### *Sag Duration*

Duration of voltage sags caused by faults at the critical distance (0.70 p.u. sag) is measured. For Dansai Substation, it's found that sag durations for both single-line-to-ground fault and three-phase fault are not in the immunity region (i.e., more than 0.50 seconds) as shown in Figures 11 and 12.

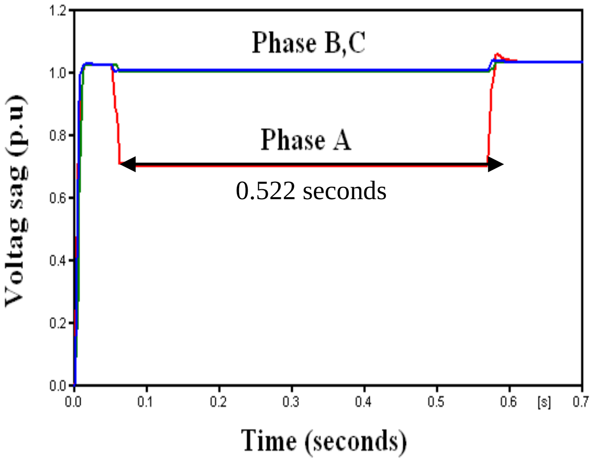


**Fig.11. Voltage Sag Duration Caused by Single-line-to-ground Fault at 7.5 km from Dansai Substation**

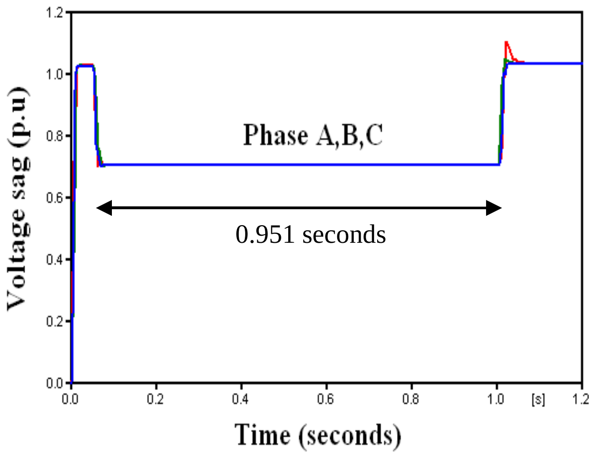


**Fig.12. Voltage Sag Duration Caused by Three-phase Fault at 20 km from Dansai Substation**

The voltage sag durations at the critical distance for both single-line-to-ground and three-phase faults of Thammasat University Substation are in the healthy zone (or less than 0.50 seconds) as shown in Figure 13. Therefore, reducing fault clearing time is unnecessary.

The feeder protection coordination of circuit breaker at the beginning of feeder, K-type expulsion fuses at near and far branches of 65 A and 40 A respectively are illustrated in Figure 14.

### *Test Results*

To reduce the fault clearing time of circuit breaker with overcurrent relay, the simulation will be done to find out the new setting values of phase and ground time-current characteristics. The concept is to reduce clearing time of voltage sag between 0.7 to 0.8 p.u. to be less than 0.5 seconds.

After simulation, the proper setting parameter for overcurrent relay are shown in Table 4 and the protection coordination after improving is displayed in Figure 15, which excludes the opening time of circuit breaker (100 ms). To make sure that expulsion fuse is blown before circuit breaker in case fault occurred downstream from fuse, reducing fuse rating to be 40 A instead of 65 A for near branch circuit.

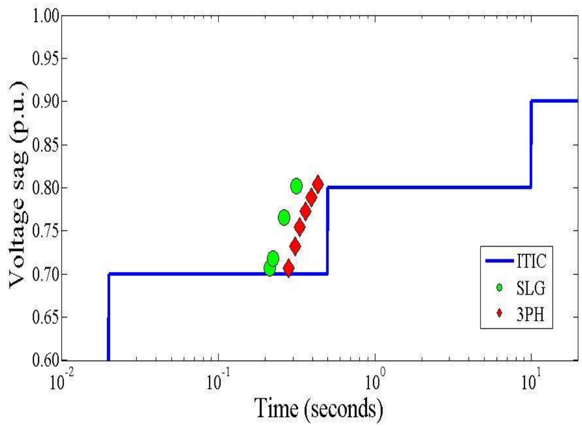


**Fig.13. Voltage Sag Caused by Faults between 0.70 to 0.80 p.u. of Thammasat University Substation**

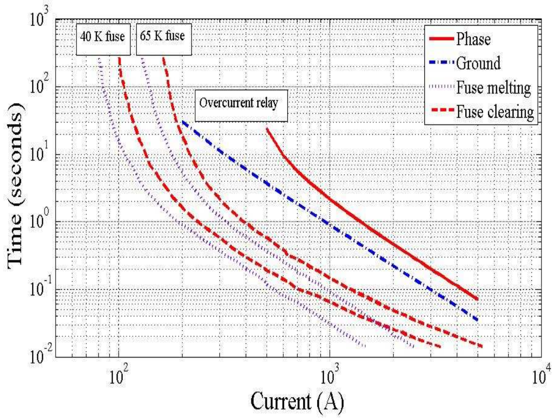


**Fig.14. Time-current Characteristics of Protective Devices Installed in Test System (Base Case)**

**Table 4. Revised Setting Parameters**

| Protection type | Characteristic curve | Pick-up current (A) | Time multiplier |
|---|---|---|---|
| Phase | Extremely inverse | 420 | 0.025 |
| Ground | Extremely inverse | 105 | 0.250 |

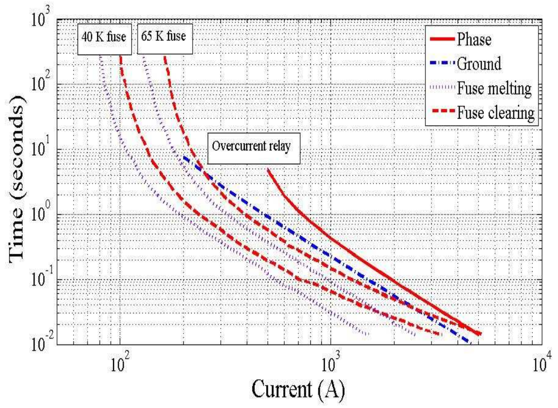


**Fig.15. Time-current Characteristics of Revised Coordination Scheme for Protective Devices Installed in Test System**

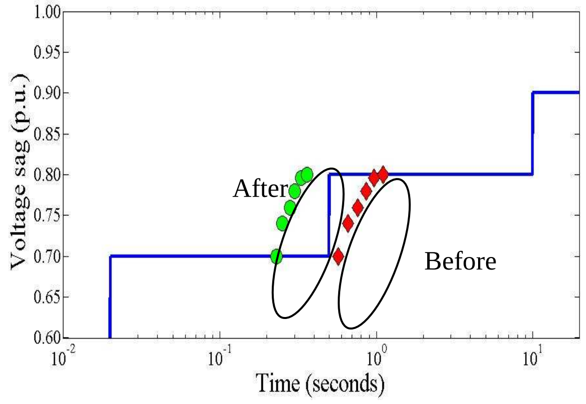


**Fig.16. Voltage Sag Mitigation for Single-line-to-ground Fault**

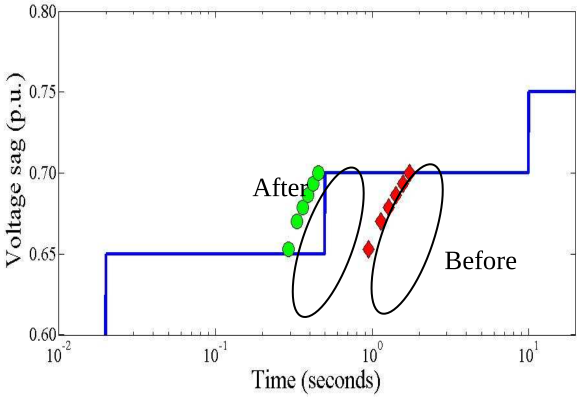


**Fig.17. Voltage Sag Mitigation for Three-phase Fault**

Figure 16 and 17 show the voltage sag mitigation results of Dansai Substation caused by both single-line-to-ground fault and three-phase fault. The votage sags are moved from the unimmunity region to the immunity region of the ITIC curve (see Figure 1).

It is confirmed from the above simulation results that the reduction of fault clearing time by the revised protective relay setting can effectively decrease voltage sag duration. For this reason, the reliability of this approach rests on the accuracy of the operating time of the protective relay and circuit breaker.

## 7. CONCLUSION

A practical method for voltage sag mitigation in PEA's distribution systems has been presented. Protective device models were developed on EMTP to study voltage sag mitigation by protection coordination. The main idea for the mitigation is achieved by changing the existing protection coordination and/or resizing the fuse rating without violating the fuse blowing scheme. The simulation results indicate that factors that affect voltage sags are fault locations, fuse sizing, overcurrent relay settings, and source impedance. Although reducing fault clearing time can mitigate voltage sags due to fault events, it may not be a viable solution for weak source systems where their critical distance is long and hence are exposed to fault events. An alternative solution to this case is to reduce source impedance, for example, by reducing transformer impedance. However, doing so increases the fault level at the substation, thus shortening lifetime of system equipment. Therefore, appropriate fault clearing time should be determined.

The proposed method can be practically implemented as long as the critical distance of a protected feeder is not too far from its substation. In addition, protection coordination with other protective devices (e.g., expulsion fuse, circuit breaker) is affected by the revision scheme. Despite such constraints, the proposed method is still attractive and, most importantly, cost-effective as no major investment cost is associated. This technique has been now implemented in the 22 kV distribution systems of Ban Pong 1 substation in Ratchaburi province and its pros and cons are under evaluation. If the outcome turns positive, this revised protection scheme will be put forward to other substations of PEA in the future.

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