Arc Flash and ZSI Analysis for Personal and Equipment Protection in Distribution System

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Abstract: The distribution system has an important role in the electric power system. This system is directly related to consumers so that continuity must be maintained. More and more customers are connected to the protection system will increase the risk of interference. Disturbances that often arise in the electric power system are short circuit. This fault can further cause arc flash, which endangers workers and equipment. Protection equipment added to the distribution system is a circuit breaker (CB) and relay. Both of this equipment have been widely used in electric power systems. To improve the performance of the relay settings, the Zone Selective Interlocking (ZSI) method is applied to the overcurrent relay (OCR) and ground fault relay (GFR) time settings. ZSI will determine priority areas that should not experience blackouts such as important equipment such as generators or big loads and minimize trips by eliminating sources of interference as soon as possible. The time setting of the ZSI method will be used as a parameter when calculating arc flash energy. The results of this energy calculation are used as a reference to determine personal protective equipment (PPE) that must be used when working in electrical areas. The combination of these two analyzes protects the system from disruption while securing the workers in it.

1 INTRODUCTION

The protection system on the electric power system is designed not only to protect equipment but also to the workers inside. Equipment safety will affect the safety of workers as well. The electrical system safety equipment that is still commonly used is a relay with the current transformer (CT) and circuit breaker (CB). The time setting of the relay is very important because the CB trip time will be a parameter in the calculation of arc energy. The faster the CB opens, the shorter the time of the arc. However, CB trip time must still follow the specified relay coordination to avoid trip errors (Dugan, 2007; Doan et al., 2009; Simms and Johnson, 2013) .

Improvements in the relay settings for the power system have been carried out, for example, by dividing the system into smaller parts. Relay settings will be based on the state of this small system so that information about the interference will be more accurate. This relay setting can also be paired with other analyzes to improve system reliability (Ma et al., 2017; Shen et al., 2019; Kanabar et al., 2017) .

The arcing analysis itself can only be done after the protection system has been well coordinated. The arc event is unique in each event. Several models have been carried out to illustrate the arc events as in (Doan et al., 2009; IEEE, 2001; Doan and Swiegart, 2003; Papallo, 2012) . Other factors that influence arcing calculations, such as grounding, isolation, switches, and the likelihood of arcing events, have also been investigated to make calculations closer to real events (Short and Eblen, 2012; Gregory and Lippert, 2012; Nelson et al., 2014) .

The arc will cause energy to damage the affected area. If there are workers who are near the short circuit location, then the impact of the arc energy can cause danger to workers. Therefore, the arc energy can be a reference for protective clothing that workers need to wear while working in voltage areas (Dugan, 2007; Doan et al., 2009; Hoagland, 2013) .

Relay coordination settings can be improvised to reduce the possibility of arcing hazards because the timing parameters of arc events can be changed through the relay settings (Simms and Johnson, 2013; Valdes and Dougherty, 2014; D'Mello et al., 2016; Walker, 2013) . One method that has been

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widely studied and used is the Zone Selective Interlocking (ZSI) method. ZSI will divide the power system into zones based on priority levels. Fault in one zone will not affect the other zones and will also minimize trip events so that power continuity will be maintained (Valdes and Dougherty, 2014; Hodgson and Shipp, 2010; Glover et al., 2012) .

This research will apply ZSI on the coordination of overcurrent relays and ground fault relays. Next, perform an arc flash analysis to determine the incident energy of the arc flash. The calculation of relay settings and arc flash analysis uses the IEEE standard, and the determination of personal protective equipment is based on the NFPA 70E standard.

The simulation is carried out on the distribution system of the Balikpapan city. The distribution system is an important part of a power system whose continuity needs to be maintained. Distribution system positions that are close to the load have the potential to experience short circuit events that must be immediately handled by workers in a voltage situation.

2 PROTECTION SYSTEM OF POWER SYSTEM

2.1 Distribution System

The power system is generally divided into four parts, namely generators, transmission lines, distribution lines, and loads. The distribution system is a very important part of the power system for two reasons, namely because it is the system closest to the consumer, and the investment costs are high. If there is a fault in the distribution system, it will directly affect consumers. Unlike when there is a disruption in the transmission system or generating system that does not directly affect consumers (Glover et al., 2012) .

2.2 Short Circuit Fault

A distribution system that is connected to many loads has a high probability of interference. Some disturbances that can arise in the distribution system such as harmonics, excess or lack of reactive power, overload, and short circuit. A short circuit event is one of the events that cause quite serious damage. A short circuit fault occurs because of connections between parts that cannot be connected. This can cause a very large current so that it can damage the electrical equipment that is around the point of fault that occurs. If a short circuit occurs, the current value will increase very quickly and is far higher than the nominal current. A short circuit can be formulated like equation 1. IF is short circuit current, VF is the voltage on the bus where the short circuit occurs, and ZF is the impedance measured from the location of the short circuit (Glover et al., 2012) .

$$I_F = \frac{V_F}{Z_F} \tag{1}$$

2.3 Relay Setting

One of the protective equipment that is commonly used is a relay. The relay will determine whether the current that is read by the current transformer is the fault current. If the detected fault current has passed through the setting, the relay will give a command to the CB to open the contact and separate the disturbed area. The relay has two settings, namely current and time. If both of these settings have been met, the relay will operate. The relay operating time must be correctly determined to ensure that when a fault occurs, the relay does not trip before other protective devices. In general, the relay can be set by selecting two parameters, namely the current pick-up or plug setting multiplier (PSM) and the operating time or time setting multiplier (TMS; Gers and Holmes, 2004) . The PSM settings of the relay can be seen in equation (2).

$$PSM = \frac{OLF \times I_{nom}}{CTR} \tag{2}$$

OLF is an overload factor whose value is determined based on the equipment being protected. Then, Inom is the nominal line current, while CTR is the primary side ratio of the current transformer (CT) / tap primary. TMS adjusts the time delay (t1) relay when operating whenever the fault current exceeds the current pick-up setting. This TMS will affect the value of the operating time of the relay. To determine the value of the time dial, equation (3) can be used.

$$t_1 = \left[\frac{k}{\beta . \left(\frac{I}{I_{SET}} \right)^{\alpha} - 1} \right] .TD \tag{3}$$

I am current flow in the line circuit, ISET is current relay setting, and the others are constant from the chosen standards.

2.4 Arc Flash Analysis

High short circuit currents can cause the emergence of high energy around the fault location. This large energy is usually called the arc flash. Arc flash can cause fire and even explosion because the arc flash is heat energy and intense light at the point of the arc. The phenomenon of an arc explosion which is a combination of a conductor and the air around a hot arc that evaporates, causing pressure, which often causes the equipment or insulation material to explode. The beginning of the arc flash appears due to arcing fault. Arcing fault itself can be defined as the flow of electric current flowing in a line that should not have current flowing. The current creates an electric arc plasma and releases a dangerous amount of energy. For the system in which the voltage under 1kV is using equation (4) and the other using equation (5; IEEE, 2001; Plaines, 2005) .

$$\log I_a = K + 0.662 \log I_{Bf} + 0.0966(V) + 0.000526(G) + 0{,}5588(V)\log I_{Bf} + 0{,}00304(G)\log I_{Bf} \quad (4)$$

$$\log I_a = 0.00402 + 0.983 \log I_{Bf} \quad (5)$$

Equation Description:

Ia = arcing fault current (kA)

K = -0,153 for open air arc, or -0,097 for enclosed arc.

IBF = bolted fault current (kA)

G = Conductor Gap (mm)

After Ia obtained, calculate the normalized incident energy using equation (6). Then calculate the incident energy by using equation (7; IEEE, 2001) .

$$\log E_n = K_1 + K_2 + 1.081 \log I_a + 0.0011G + 0.000526(G) \quad (6)$$

$$E = 4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \quad (7)$$

Equation Description:

En = Normalized incident energy (cal/cm2)

E = Incident Energy (cal/cm2)

K1 = -0,792 for open air arc, or -0,555 for enclosed arc.

K2 = 0 for ungrounded system, -0,113 for grounded system.

t = Arc durations (s)

= 1,0 for voltage above 1 kV, or 1,5 for voltage below 1 kV

D = Distance from the arc (mm)

x = Distance exponent from IEEE 1584 standard

Table 1: Personal Protective Equipment Categories

Category	Cal/cm2	Clothing
0	1.2	Untreated Cotton
1	4	Flame retardant (FR) shirt and FR pants
2	8	Cotton underwear FR shirt and FR pants
3	25	Cotton underwear FR shirt, FR pants, and FR coveralls
4	40	Cotton underwear FR shirt, FR pants, double layer switching coat dan pants

2.5 Determining Personal Protective Equipment (Ppe) Categories

Arc flash hazard category can be determined based on the energy that occurs. Flash hazard arcs are categorized into five categories and can be seen in Table 1. The hazard category will determine the standard for using PPE that refers to the NFPA 70-E standard. This standard will describe the PPE needed by workers to work in areas that have the potential for arc flash. The higher the hazard category, the PPE recommendation will be more complete, closed, and safe when used by workers. The highest energy level of the standard is 40 cal / cm2, and if the energy that occurs is more than that, then the danger that arises is very dangerous (NFPA, 2003) .

2.6 Zone Selective Interlocking Method

Protection systems using relays have been developed, and one of them uses a protection zone. Zone Selective Interlocking (ZSI) is a communication scheme used with electronic trip units and electronic protective relays for circuit breakers to increase the level of protection in power distribution systems. Zones are classified according to their location downstream of the main circuit protection devices, which are generally defined as zone 1.

The system will be made into several protection zones. As an illustration, the power system has 3 zones in series connected from zone 3 to 1. If using normal relay coordination, when interference occurs in zone 3, CB in zone 3 will trip, then CB in zone 2 will trip and continue to zone 1. This will disrupt services in zones 2 and 1. ZSI allows interference to be eliminated by using CB in its protection zone without disturbing others (Simms and Johnson, 2013; Walker, 2013; Hodgson and D. Shipp, 2010; Glover et al., 2012)

3 SIMULATION AND ANALYSIS

This research began by collecting data from the distribution system. The simulation is done using ETAP software. The data that has been generated will be used as a parameter in the simulation. Some of the simulations performed are power flow simulation, short circuit simulation, then OCR, and GFR coordination simulation. OCR and GFR simulations are carried out using the ZSI method in it. Next, the simulation results are used as parameters to determine the arc flash energy. Finally, from the calculation results, the level of PPE must be determined. The explanation of each step will be explained as follows.

Table 2: The Result of Load Flow and Short Circuit Simulation

Bus ID	IFL (A)	I Max		I Min.
		ISC3φ (kA)	ISC1φ (kA)	ISC2φ (kA)
Bus 1	4.2	2.117	0.987	1.169
Bus 2	1.3	2.126	0.989	1.172
Bus 3	5.5	2.129	0.99	1.173
Bus 4	10.2	2.149	0.996	1.179
Bus 5	85.7	2.152	0.997	1.18
Bus 6	12.6	2.167	1.001	1.185
Bus 7	18.5	2.199	1.01	1.196
Bus 8	39.8	2.208	1.012	1.199
Bus 9	21.3	2.202	1.011	1.197
Bus 10	13.9	2.185	1.006	1.191
Bus 11	8.5	2.173	1.002	1.187
Bus 12	5.4	2.173	1.002	1.187
Bus 13	46.6	2.216	1.015	1.202
Bus 14	4.2	2.213	1.014	1.201
Bus 15	49	2.225	1.017	1.205
Bus 16	54.1	2.241	1.022	1.211
Bus 17	95.1	2.309	1.043	1.238
Bus 18	119.1	2.316	1.045	1.241
Bus 19	24	2.304	1.042	1.237
Bus 20	21	2.289	1.037	1.232
Bus 21	135	2.358	1.06	1.262
Bus 22	177.4	2.363	1.061	1.264
Bus 23	42.3	2.36	1.06	1.263
Bus 24	37.8	2.35	1.058	1.26
Bus 25	35.7	2.347	1.057	1.259
Bus 26	256.8	2.364	1.062	1.265
Bus 27	79.4	2.344	1.055	1.257
Bus 28	44.8	2.338	1.054	1.254
Bus 29	39	2.326	1.05	1.25
Bus 30	22.1	2.273	1.035	1.232
Bus 31	13.9	2.225	1.022	1.216
Bus 32	262.5	2.373	1.068	1.276
Bus 33	288	2.455	1.137	1.403

3.1 Power Flow Simulation

In the initial stage, the system will be modeled according to real conditions based on data that has been obtained at the data collection stage using ETAP software. Data needed include voltage, power, and impedance of each piece of equipment.

The next step is the simulation of power flow. This simulation is done as a reference that the system is running in good condition. So it can be seen that the flow of power from the source to load can be distributed normally. The power flow

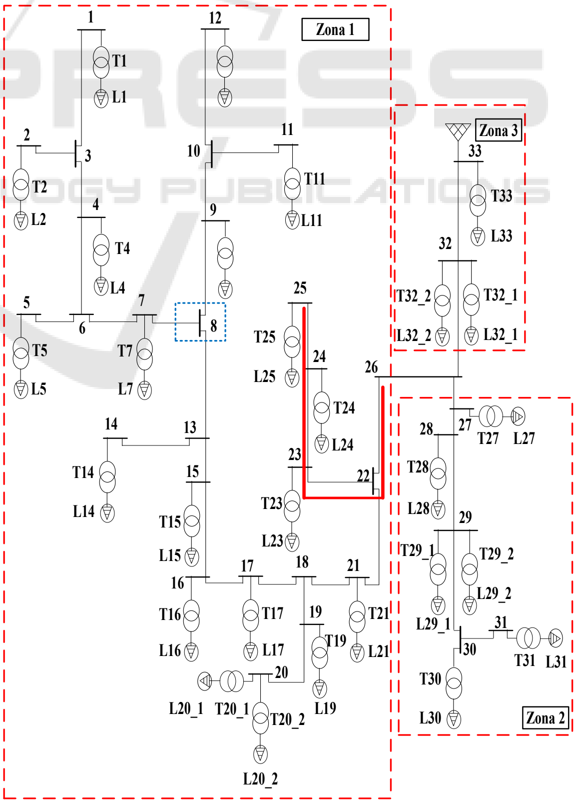

Figure 1: Distribution System

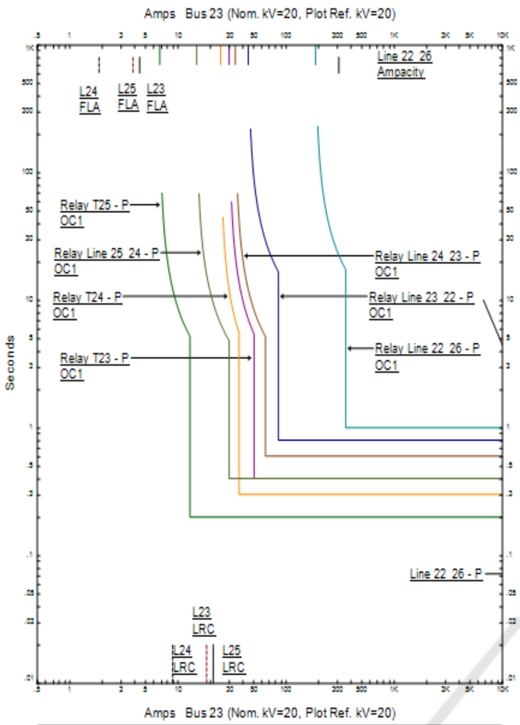

Figure 2: Relay Coordination

The Simulation will also get a full load current (IFL), which will be used for OCR and GFR settings. Besides, power flow simulation is also carried out to determine the value of voltage, power, and full load current on each bus at the steady-state condition. Power flow simulation is done by Newton Raphson Modification Method.

3.2 Short Circuit Simulation

The *Inom* of equation (2) can come from overload or short circuit fault, so the next simulation is a short circuit simulation. The calculated short-circuit current is a maximum 3-phase short circuit, a minimum of 2 phases, and a maximum of 1 phase to ground. A maximum of 3 phase short circuit and minimum 2 phase will be used for OCR settings, which will overcome the overload and phase short circuit. While phase to ground short circuit will be obtained from a single-phase short circuit simulation and then become a parameter for setting GFR. The short circuit current obtained is presented in Table 2.

3.3 OCR and GFR Coordination using ZSI Method

Relays installed in each primary part of the transformer are 35 relays and 31 relays in the line. Each relay will be equipped with a current transformer to read the value of the current flowing in the line or equipment. Besides, the relay also has a CB that will open if it gets a trigger from the relay. The system configuration can be seen in Figure 1.

Short circuit data previously used to determine the current and time settings of the protection relay. OCR will be used to protect equipment from overload current and short circuit 3 phase, two-phase, or interphase. For overload disturbances, the current setting uses equation (2), and the time setting uses equation (3). While for a short circuit, the current setting also uses equation (2), but the time setting is set by itself. This time setting must be coordinated between relays. The time interval between relays must be between 0.2 - 0.4 seconds. The shortest time is placed in the load, and the value increases if it approaches the source.

Single-phase disturbance to the ground is protected using GFR. This relay also has two settings, namely the current based on equation (2) and the time setting determined based on the coordination between relays. The time between relays must also be between 0.2 - 0.4 seconds. GFR relay coordination is carried out at one voltage level, so at different voltage levels, the coordination used is also different. Relay current settings are determined based on single-phase fault current to the ground and special charging lines for relays in the line.

Figure 2 shows the current-time curve against the OCR relay for L25 to Bus26 loads (marked with a thick red line in Figure 1). There are seven relays connected between the two devices, namely Relay T25, Relay Line 25_24, Relay T24, Relay Line 24_23, Relay T23, Relay Line 23_22, and Relay Line 22_26. For other equipment, settings are done in the same way.

Based on Figure 2, two curves are combined into one, firstly the curve for overload disturbance is in the form of an inverse and the curve for a short circuit which is in a vertical straight line. Horizontal lines indicate the time delay of the relay for short circuit fault with a fixed value. If the fault current meets the current setting of the relay, the relay will give a signal to the CB after the delay time is met. While the time for overload depends more on the amount of overload current, the greater the current that appears, the faster the relay's working time. The x-axis represents the amount of current, and the y-axis represents the amount of time.

Table 3: Relay Setting of Figure 2

Relay	ISET for overload (A)	ISET for SC (A)	t (s)
Relay T25	2	2032.502	0.2
Relay Line 25_24	4	2035.1	0.4
Relay T24	18	2035.1	0.3
Relay Line 24_23	28	2043.76	0.6
Relay T23	46	2043.76	0.4
Relay Line 23_22	GH	2046.358	1
Relay Line 22_26	56	2047.224	1.4

Besides, the relay current setting must be higher than the inrush current transformer or be located behind the relay curve. This shows that a high starting transformer current will not make the relay works. But if the high current can cause damage to the transformer, the relay will work. Each equipment has a damage curve that states the equipment insulation resistance, and relay settings must be made before the damage curve so that the relay can work before the equipment insulation is damaged.

After all parts of the system have been secured using a relay, then the ZSI method is added. The system is divided into 3 zones, as in Figure 1. If there is a disturbance in one zone, then the other zone must not experience a trip too. The fault that occurs at load L23 will cause Relay T23 to work, followed by Relay Line 23_22 and Relay Line 22_26. After the Relay Line 22_26 causes a trip, no CB can trip again due to the relay. This is because the last Relay in the same zone as the L23 load is the Relay Line 22_26. Trip events on Relay Line 22_26 will lock Relay Line 26_28 and Relay 26_27 to remain open. This also applies to interference in other zones. Relay settings can be seen in Table 3.

ZSI is also enforced in one zone as in Bus 8 (blue dotted line in Figure 1). The area from Bus 1 to Bus 7 will be zone 1a, and the area of Bus 9 to Bus 11 will be zone 1b. Because CB that can trip is limited, it must be well ensured that the relay can detect interference as soon as possible and work effectively to eliminate fault so that it does not spread and trigger other relays to work.

3.4 Arc Flash Analysis and PPE Categories

Arc flash analysis is done by calculating the amount of energy that appears when the arc flash occurs. By using the current arc value in equation (5), a normalized event energy value (En) can be calculated using equation (6). Finally, the event energy (E) is solved using equation (7). The time setting of the Relay plus the operating time of the CB will be the parameter of the arc flash time duration. The longer the arc flash event, the higher the arc flash energy that appears. Other parameters, such as the values of K, G, D, and x, adjust the real situation.

The results of incident energy will be used as a reference in determining PPE requirements based on Table 1. The energy incident and PPE level settings can be seen in Table 4.

Table 4: The Result of Arc Flash Analysis

ID Bus	t (s)	E (cal/cm2)	Level PPE
Bus 1	0.5	1.195761	0
Bus 2	0.5	1.201164	1
Bus 3	0.7	1.684151	1
Bus 4	0.9	2.186959	1
Bus 5	0.7	1.703491	1
Bus 6	1.1	2.696746	1
Bus 7	1.3	3.237097	1
Bus 8	1.3	3.251178	1
Bus 9	1.1	2.743053	1
Bus 10	0.9	2.225909	1
Bus 11	0.5	1.229401	1
Bus 12	0.5	1.229401	1
Bus 13	1.5	3.765803	1
Bus 14	1.5	3.760386	1
Bus 15	1.5	3.782058	1
Bus 16	1.5	3.810964	1
Bus 17	1.5	3.93396	1
Bus 18	1.5	3.946634	1
Bus 19	1.1	2.878266	1
Bus 20	0.7	1.818955	1
Bus 21	1.5	4.02273	2
Bus 22	1.5	4.031795	2
Bus 23	1.1	2.952661	1
Bus 24	0.7	1.870507	1

Bus 25	0.5	1.334264	1
Bus 26	1.5	4.033608	2
Bus 27	1.5	3.997355	1
Bus 28	1.3	3.454952	1
Bus 29	1.1	2.907479	1
Bus 30	0.7	1.805447	1
Bus 31	0.5	1.260686	1
Bus 32	1.7	4.589918	2
Bus 33	1.7	4.758638	2

4 CONCLUSION

The distribution system requires a protection system because of the location of the distribution system that is connected to many loads will increase the risk of interference. Relays can be added to the distribution system as protective equipment. Relays are equipped with supporting equipment such as CT and CB. Relay settings need to be coordinated so that there are no trip errors, and disturbances can be isolated immediately. ZSI method is added to the relay coordination to minimize the number of CB that trip. ZSI divides the distribution system into 3 zones where a disturbance in one zone will not affect the other zones. After relaying the coordination with ZSI, the relay will work time, which is the duration of the short circuit before the CB trip. During the duration of this short circuit, there is energy released due to high currents or known as arc flash. Arc flash is very dangerous not only for equipment but also for workers. By knowing the value of energy released during short circuit events, the protective clothing that workers must use can also be determined. From the distribution system analyzed, it is known that the highest PPE level is level 2.

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