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Arc Flash Faults Calculations, Hazard Analysis and Reduction Methods

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Abstract: *Nowadays, the consume of electrical energy has increased, so it has brought more high-power systems and more need for electrical energy continuity. For that reasons, faults effects and damages get more destructive. The increasing need for electrical energy and continuity has led to the analysis, reduction and take necessary precaution for potential hazards in electrical power systems operation and maintenance. One of the important faults which cause power failure on electrical power systems is arc faults. The arc can be defined as an electrical discharge that is happened between two electrodes in insulation materials like air, gas, ex. In electrical power systems, during arc faults the short circuits which is happened due to various reasons arise uncontrollable energy, heat, pressure and light. Then it is also called arc flash faults. Because of this incident energy and heat which appear in arc faults can damage switching equipments, can cause loss of life and economic damage. Therefore, in electrical power systems arc fault current and incident energy calculations shall be done, hazard analysis must be considered and arc incident energy should be reduced with taking related precaution. In this work, arc flash calculations methods are explained and arc incident energy reduction methods are examined. Additionally, in a simple power system arc flash calculation and risk analyses done with using Electrical Power System Analysis and Operation Software (ETAP).*

Keyword: *arc fault; arc flash fault; arc incident energy calculation methods; arc incident energy reduction*

1. INTRODUCTION

Arc flash event can be defined as a rapid release of energy, caused by an arcing fault that results from a short circuit between two conductors. Because of the that high energy release, arc faults have significant effect. This effect can be described as thermal impact, pressure wave, flying particles, toxic impact, sound and light. These can hazard the personnel and equipment. Therefore, arc faults lead to economic damages, voltage stability problems, power loss and quality problems on power systems. To minimize the risk and hazard of the arc faults, arc flash calculations shall be done, risk must be analyzed and related precaution should be taken.

In most of the previous researches, the arc flash calculations are presented and focused on one of the arc incident energy reduction methods. On the other hand, there are so many researches which are just explained some arc incident energy reduction methods.

In [1], general overview of the arc flash analysis and measures to avoid hazards are provided. Additionally, temporary change of relay coordination technique is investigated as a solution for the substations in which arc-flash hazard level is beyond acceptable levels. They have made the calculation and simulation with DigSilent. In B. Gordon, K. Carr and N. Graham's paper, comprehensive approach to classifying the electrical shock hazards of all types of electricity, including various waveforms and various types of sources of electrical energy is presented. Additionally, arcs are categorized according to types and hazards. [2]

The arc flash hazard assessment in distribution system including Distributed Generations (DGs) is presented in [3]. It showed that the fault current contribution from DGs decreases the arcing time consequently decreases the incident energy. In [4], the effects of critical parameters that influence incident energy level at different locations in a power system are analyzed with ETAP and different mitigation techniques are also proposed to reduce incident energy. In another paper, voltage stability importance is pointed out which is really important for power sys-

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tems. Additionally, optimal placement study of Distributed Generators (DG) is presented for reducing the power loss and improve voltage stability. [5] Moreover in [6], for power system stability, optimal reactive power control using Artificial Bee Colony Algorithm is presented. As mentioned, arc flash faults can cause also quality problems. [7], has presented extensive study of quality problems in railway transportation systems.

In [8], causes and characteristics of arc-flash faults and overview of mitigation techniques of arc flash hazards are shown. Zone selective interlocking system is explained in detail. In another paper [9], The optical arc-flash detection (AFD) technology is selected and analyzed for arc flash protection. It showed that with using AFD relay, incident energy can be reduced. In R. Walsch and M. Price's paper, a method has presented which is using a MV controllable fuse to mitigate the incident energy on the equipment connected to the transformer secondary. [10]

Various opportunities to prevent arcing faults are presented, but mostly focused on protection for the pressure wave in J.A Kay and L. Kumpulainen's paper. Additionally, A combination of arc eliminator and current-limiting fuses has also been suggested for providing maximal protection, by minimizing the thermal impact, pressure wave, and even the mechanical stress caused by the arc flash fault. [11]

In this paper arc flash calculations are presented; arc flash faults precautions and hazard mitigation methods are classified as before arc fault and after arc fault. In addition, a sample arc flash calculation is performed for a simple power system using ETAP.

2. ARC FLASH CALCULATION METHODS

In this chapter, calculation method, according to IEEE 1584-2002 is explained with details, followed by the calculations with Lee Method. A summary table of methods is shown in Table I.

TABLE I: ARC FLASH CALCULATION METHODS

Arc Flash Calculation Methods
IEEE 1584-2002, "Guide for Performing Arc Flash Calculations" [12]
Lee, "The Other Electrical Hazard: Electrical Arc Flash Burns" [12]-[13]

IEEE 1584-2002 calculates incident energy and arc flash boundary for: 208 V to 15 kV; three-phase; 50 Hz to 60 Hz; 700 A to 106,000 A short-circuit current; and 13 mm to 152 mm conductor gaps.

Lee Method calculates incident energy and arc flash boundary for arc in open air; conservative over 600 V and becomes more conservative as voltage increases. Mostly, it is used for applications more than 15 kV.

Apart from these, R.L. Doughty, T.E. Neal and H. Floyd have showed equations in their paper [14] that calculates incident energy for three-phase arc on systems rated 600 V and below; applies to short-circuit currents between 16 kA and 50 kA. Additionally, for DC systems, R. Ammerman, T. Gammon, P. Sen and P. Nelson's paper [15] is showed DC arc models and incident energy calculations, in another paper from D. Doan [16] has given equations for incident energy calculation in DC systems rated up to 1000 V.

In chapter 4, arc flash calculations are presented for a sample system. In that calculations IEEE 1584-2002 and Lee method is used. Therefore, in the following parts, these methods are explained in detail.

2.1 IEEE 1584-2002 Method

IEEE Std 1584-2002 contains calculation methods developed through testing by several sources to determine boundary distances for unprotected personnel and the incident energy at the working distance for qualified personnel working on energized equipment. The incident energy level can be used to determine the proper personal protective equipment (PPE) required for personnel.

The equations developed in the IEEE standard assess the arc flash hazard based on the available (bolted) fault current, voltage, clearing time, equipment type, grounding, and working distance. The working voltage is also used to determine other variables.

The equations have other variables that account for grounding, equipment type, and construction. This method can also determine the impact of certain current limiting low voltage fuses as well as certain types of low voltage breakers. It is an improvement over the previous work in that the calculations can be applied over a large range of voltages.

2.1.1 Determine the Arcing Current

According to IEEE 1584-2002, arcing current can be determined. For calculating the arc flash current, equations are shown in Equations 1 and 2 [12];

For applications under 1000V;

$$\log_{10} I_a = K + 0.662 \log_{10} I_{bf} + 0{,}0966\, V + 0{,}000526\, G + 0{,}5588\, V(\log_{10} I_{bf}) - 0{,}00304\, G\, (\log_{10} I_{bf}) \qquad (1)$$

For applications 1000V and higher;

$$\log_{10} I_a = 0{,}00402 + 0.983 \log_{10} I_{bf} \qquad (2)$$

where I_a is the arcing fault current [kA], K is the constant that –0.153 for open configurations or –0.097 for box configurations, I_{bf} is the bolted fault current for three-phase faults (symmetrical RMS) [kA], *V* is the system voltage [kV], *G* is the gap between conductors [mm]

2.1.2 Determine the Incident Energy

Arc flash incident energy calculation is very important for arc flash hazard analysis. For calculating the arc flash incident energy, equations are are shown in Equations 3 and 4 [12];

First find the $\log_{10}$ of the incident energy normalized. This equation is based on data normalized for an arc time of 0.2 seconds and a distance from the possible arc point to the person of 610 mm.

$$\log E_n = K_1 + K_2 + 1.081 \log I_a + 0.0011\, G \qquad (3)$$

$$E_n = 10^{\log En}$$

where E_n is the incident energy normalized for time and distance [J/cm^2], K_1 is -0,792 (for open configurations) or -0,555 (for box configurations), K_2 is 0 (for ungrounded or high resistance grounded system) or -0,113 (for grounded systems), *G* is the gap between conductors [mm]

Then, incident energy formula is given below;

$$E = 4{,}184 \times C_f \times E_n \times \frac{t}{0{,}2} \times \left(\frac{610}{D}\right)^x \qquad (4)$$

where *E* is the incident energy [J/cm^2], C_f is the calculation factor (for V> 1kV: 1, for V<1kV: 1,5), E_n is the incident energy normalized for time and distance [J/cm^2], *t* is the arcing time [seconds], *D* is the distance from the possible arc point to the person [mm], *x* is the distance factor

Tables for typical bus gap (G), typical working distance (D) and distance factor (x) is given in Table II, Table III and Table IV, respectively.

TABLE II: TYPICAL BUS GAPS (G)

Classes of Equipment	**Typical bus gaps [mm]**
15 kV switchgear	152
5 kV switchgear	104
Low-voltage switchgear	32
Low-voltage MCCs and panelboards	25
Cable	13
Other	not required

TABLE III: TYPICAL WORKING DISTANCE (D)

Classes of Equipment	**Typical working distance [mm]**
15 kV switchgear	910
5 kV switchgear	910
Low-voltage switchgear	610
Low-voltage MCCs and panelboards	455
Cable	455
Other	to be determined in field
*typical working distance is the sum of the distance between the worker standing in front of the equipment to the potential arc source inside the equipment	

TABLE IV: DISTANCE FACTOR (x)

System voltage [kV]	**Equipment type**	**Typical gap between conductors [mm]**	**Distance factor (x)**
0,208-1	Open air	10-40	2,000
	Switchgear	32	1,473
	MCC and panels	25	1,641
	Cable	13	2,000
>1-5	Open air	102	2,000
	Switchgear	13-102	0,973
	Cable	13	2,000
>5-15	Open air	13-153	2,000
	Switchgear	153	0,973
	Cable	13	2,000

2.1.3 Determine the Arc Flash Boundary

The flash boundary is the distance from an arcing fault where the incident energy is equal to 1.2 cal/cm^2. Equation 5 is for determining the arc flash boundary. [12]

$$D_B = \left[4{,}184 \times C_f \times E_n \times \left(\frac{t}{0{,}2}\right) \times \left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} \qquad (5)$$

where D_B is the distance of the boundary from arcing point [mm], C_f is the calculation factor (for V>1kV ;

1, for V<1kV; 1,5), E_n is the incident energy (cal/cm2) normalized for time and distance [J/cm^2], V is the system voltage [kV], E_B is the incident energy at the boundary distance [J/cm^2] (5 J/cm^2), t is the arcing time [seconds], x is the distance factor from Table III, I_{bf} is the bolted fault current for three-phase faults (symmetrical RMS) [kA]

2.2 Lee Method

For many years, the Lee Method has taken its place in the literature as the only method for arc flash calculations. Its biggest limitation is that it does not include a method of finding arc current, which is very important for cases under 1000 V. In addition, it does not provide a calculation method within the arcs formed in the closed environment, it is another disadvantage especially for calculations in systems above 1 kV. This method should be use where the IEEE 1584 Method is not suitable, such as those in open air and applications in more than 15 kV [12]-[13].

2.2.1 Determine the Incident Energy

For cases where voltage is over 15 kV, or gap is outside the range of the model, Lee Method should be use for determining the incident energy with following Equation 6;

$$E = 2{,}142 \times 10^6 \times V \times I_{bf} \times \left(\frac{t}{D^2}\right) \tag{6}$$

where E is the incident energy [J/cm^2], V is the system voltage [kV], t is the arcing time [seconds], D is the distance from the possible arc point to the person [mm] (Table II), I_{bf} is the bolted fault current for three-phase faults (symmetrical RMS) [kA]

2.2.2 Determine the Arc Flash Boundary

According to Lee Method Arc Flash Boundary can be calculated with following Equation 7;

$$D_B = \sqrt{2{,}142 \times 10^6 \times V \times I_{bf} \times \left(\frac{t}{E_B}\right)} \tag{7}$$

where D_B is the distance of the boundary from arcing point [mm], V is the system voltage [kV], I_{bf} is the bolted fault current for three-phase faults (symmetrical RMS) [kA], t is the arcing time [seconds], E_B is the incident energy at the boundary distance [J/cm^2] (5 J/cm^2).

3. ARC FLASH HAZARD REDUCTION METHODS

Arc flash faults hazards prevention and mitigation methods are presented in this section of the paper. For better classification; these methods are explained in 2 major part as shown in Table V, such as before arc fault and after arc fault.

TABLE V: ARC FLASH HAZARD REDUCTION METHODS

Before Arc		After Arc
Arc Prevention Methods		Arc Effect Reduction and Protective Methods
Arc Prediction Methods		Arc Elimination Methods

3.1 Before Arc

Arc flash faults can damage electrical equipment and personnel, this damage might have destructive effect. Therefore, firstly arc faults preventions precautions should be taken, secondly with using developing technology like sensors arcs should be predicted and prevented.

3.1.1 Arc Prevention Methods

Arc prevention methods are quite important for electrical systems. These can be summarized in under following titles; education, design, high resistance grounding, insulated or bare conductor, maintenance, determining the working distance and warning labels.

For determining the working distance; boundaries are explained shortly according to NFPA 70E 2015 [17]. These values can also be determined according to tables in NFPA 70E 2015. Boundaries are in Figure 1 and sample warning label is on Figure 2 shown.

Arc Flash Boundary: When an arc flash hazard exists, an approach limit at a distance from a prospective arc source within which a person could receive a second-degree burn if an electrical arc flash were to occur. A second-degree burn is possible by an exposure of unprotected skin to an electric arc flash above the incident energy level of 5 J/cm^2 (1.2 cal/cm^2).

Limited Approach Boundary: An approach limit at a distance from an exposed energized electrical conductor or circuit part within which a shock hazard exists.

Restricted Approach Boundary: An approach limit at a distance from an exposed energized electrical conductor or circuit part within which there is an increased likelihood of electric shock, due to electrical arc-over combined with inadvertent movement, for personnel working near the energized electrical conductor or circuit part.

3.1.2Arc Prediction Methods

Arc prediction methods are important as much as arc prevention methods. In some situations, arc could happen even if you take all necessary precautions. Therefore, if you could able to predict it, just before it happens, you can minimize the risk and hazards of the arc flash. Arc flash can be detected by analysis of phase currents, based on zero sequence voltage or current differential and sensor technologies such as RF Antenna, piezoelectric sensor, ultraviolet sensor, Rogowski coil, thermal sensor, chemical analyzers, light sensor, etc. A sample sensor-based protection is shown on Figure 3.

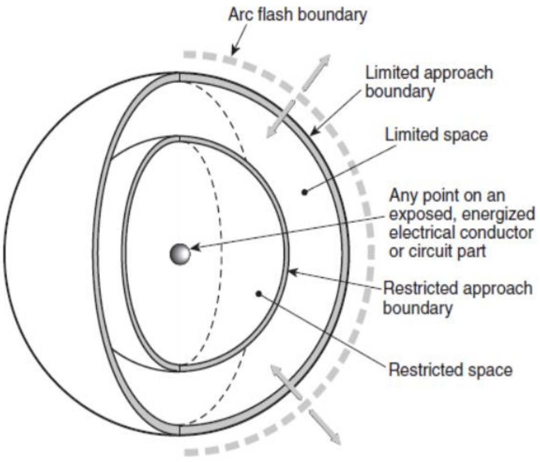
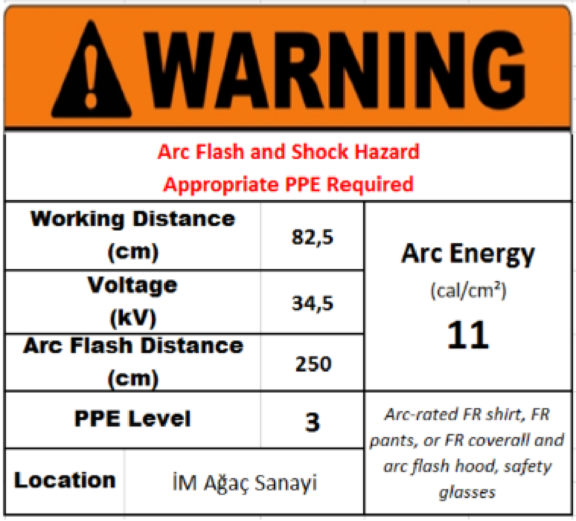


Figure 1: Limits of approach [17]



WARNING

Arc Flash and Shock Hazard
Appropriate PPE Required

Working Distance (cm)	82,5	Arc Energy (cal/cm^2) 11
Voltage (kV)	34,5	
Arc Flash Distance (cm)	250	
PPE Level	3	*Arc-rated FR shirt, FR pants, or FR coverall and arc flash hood, safety glasses*
Location	İM Ağaç Sanayi	

Figure 2: sample of arc flash warning label [1]

3.2 After Arc

Even if you take all necessary preventive precautions, and try to predict and prevent the possible arc, arc flash faults can happen quite often. Therefore, methods for minimizing arc flash fault hazard after it happened, getting more important.

3.2.1 Arc Effect Reduction and Protective Methods

Preventive or predictive measures cannot eliminate the risk of all arc faults. Direct human interaction or equipment malfunction may still lead to serious faults. That is the reason, why arc effect reduction and protective methods are significant.

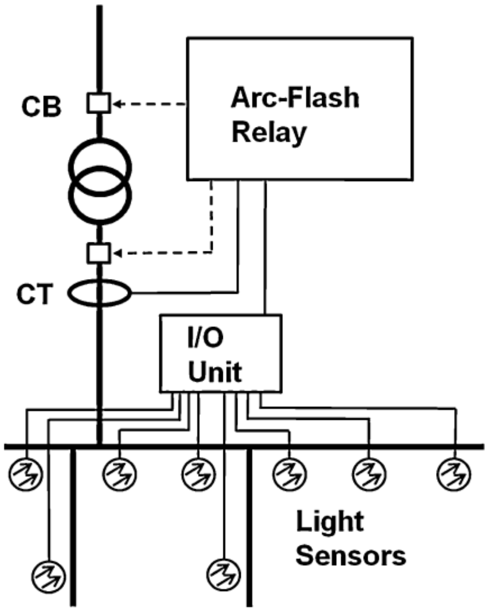


Figure 3: An example of a light and overcurrent detection-based arc-flash protection system. [18]

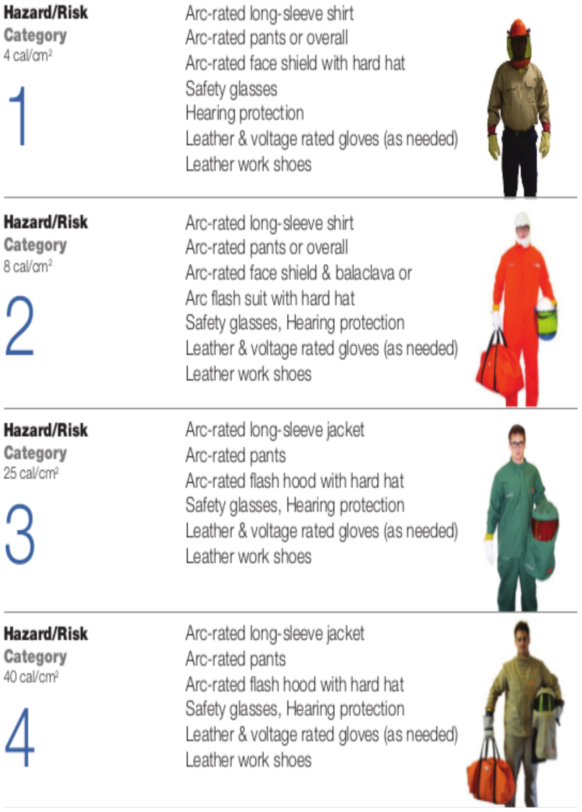
The hazard of the arc could be measured according to arc incident energy in that point. So, the calculation of the arc flash incident energy is for evaluating needed safe working distances and personal protective equipment (PPE) for employees. Arc flash energy is mainly dependent on voltage, distance, arc current and arcing time. The main factors that can be changed in practice are arc current and arcing time. Because the system voltage and working distance are not easily changeable factors. Therefore, arc effect reduction and protective methods can be summarized as follows:

-reducing or limiting arc current methods
-reducing arcing time methods
-using special protective equipment for arc faults
-using personal protective equipment (PPE)

3.2.2 Arc Elimination Methods

We can say that there are basically three different equipment or technologies that extinguish the arc; fuses, breakers and arc eliminators. It’s obvious that fuses and breaker are really important for system’s protection especially for arcing time.

The arc eliminators are equipment that extinguish the arcs very quickly by creating a parallel short circuit. Additionally, it mitigates the pressure wave which happens after arc. Arc eliminators are not widely used because they are defined as optional to provide a high level of protection in the IEC 62271-200 standard. [11]



Hazard/Risk Category 4 cal/cm²
1
- Arc-rated long-sleeve shirt
- Arc-rated pants or overall
- Arc-rated face shield with hard hat
- Safety glasses
- Hearing protection
- Leather & voltage rated gloves (as needed)
- Leather work shoes

Hazard/Risk Category 8 cal/cm²
2
- Arc-rated long-sleeve shirt
- Arc-rated pants or overall
- Arc-rated face shield & balaclava or
- Arc flash suit with hard hat
- Safety glasses, Hearing protection
- Leather & voltage rated gloves (as needed)
- Leather work shoes

Hazard/Risk Category 25 cal/cm²
3
- Arc-rated long-sleeve jacket
- Arc-rated pants
- Arc-rated flash hood with hard hat
- Safety glasses, Hearing protection
- Leather & voltage rated gloves (as needed)
- Leather work shoes

Hazard/Risk Category 40 cal/cm²
4
- Arc-rated long-sleeve jacket
- Arc-rated pants
- Arc-rated flash hood with hard hat
- Safety glasses, Hearing protection
- Leather & voltage rated gloves (as needed)
- Leather work shoes

Figure 4: PPE levels and appropriate equipment [1]

4. ARC FLASH ANALYSIS ON SAMPLE SYSTEM

A sample system is selected from industry and analyzed with ETAP Software. (Electrical Power System Analysis & Operation Software) for arc flash calculations.

This system is connected to 154 kV power grid through 6 MVA 10/34.5 kV and 100 MVA 34,5/154 kV Transformer.

From 10 kV Bus, there is a 7.5 MVA Generator connection. Additionally, there are five Distribution Transformers 10/0.4 kV which have different loads connected.

The single-line diagram of the system can be seen on Figure 5.

Two scenarios for arc flash calculations are taken into account at simulations;

Scenario 1: Generator is not connected from Bus 4, so loads are just fed from Power grid.

Scenario 2: Generator is connected from Bus 4 and around 3 MVA power supplied to the system.

According to these different scenarios, 3 phase short-circuit fault and arc flash analyze on Bus 4 and Bus 10 are realized and obtained results are compared with each other. The numerical results are given in Table VI.

From the Table VI, it can be seen that; on scenario 2 when the generator is connected to the system, it has a significant effect on short circuit current consequently to arc current and arc flash incident energy. Especially on Bus 4, short circuit current is %53 and arc fault current is %52 increased. On the other hand, on Bus 10, short circuit current is %13,6 and arc fault current is %11,4 increased. The change on arc fault current has also caused a change on the arc flash incident energy, so incident energy is changed on Bus 4 from 1,55 cal/cm^2 to 2,85 cal/cm^2 and on Bus 10 from 4,45 cal/cm^2 to 5,01 cal/cm^2. The increase of an arc flash incident energy means more damage to equipment and personnel. Therefore, arc flash boundary is also changed on Bus 4 from 103,63 cm to 140,81 cm and on Bus 10 from 88,08 cm to 93,26 cm.

TABLE VI: COMPRASION TABLE ACC. TO SCENARIO AND LOCATION

	Scenario 1 (Gen. is not connected)		**Scenario 2 (Gen. is connected)**	
3-phase short circuit location	Bus 4	Bus 10	Bus 4	Bus 10
3-phase short circuit current [kA]	4,7	38,91	7,2	44,24
Arc fault current [kA]	4,62	19,66	7,03	21,92
Arc flash incident energy [cal/cm^2]	1,55	4,45	2,85	5,01
PPE Level	1	2	1	2
Arc flash boundary [cm]	103,63	88,08	140,81	93,26

Additionally, it’s obvious that in different points arc flash levels are distinctive. For instance, even if Bus 10 has 0,4 kV, it has PPE level 2, because of high fault current on low voltage part.

According to scenario 2, when the Bus 4 and Bus 10 are faulted, arc flash analyses are realized, arc flash level, incident energy, fault clearing time (FCT) and arc current are presented on Figure 6. Sources contribution to the arc current can be seen as well.

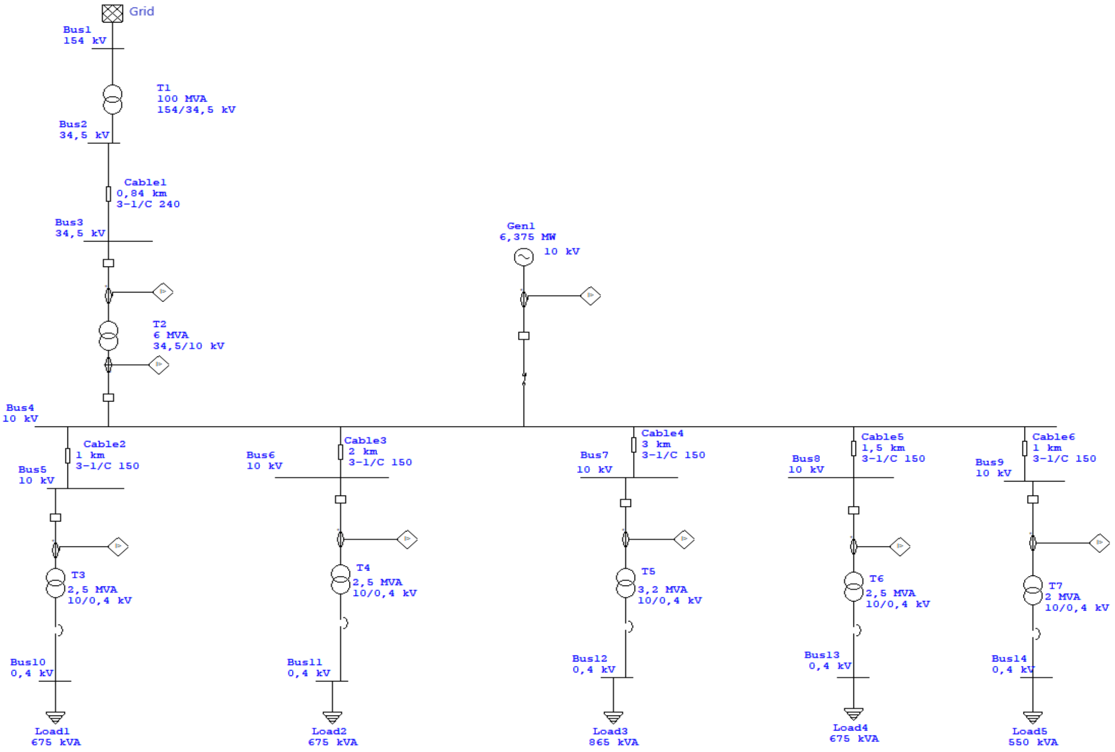


Figure 5: System's single-line diagram

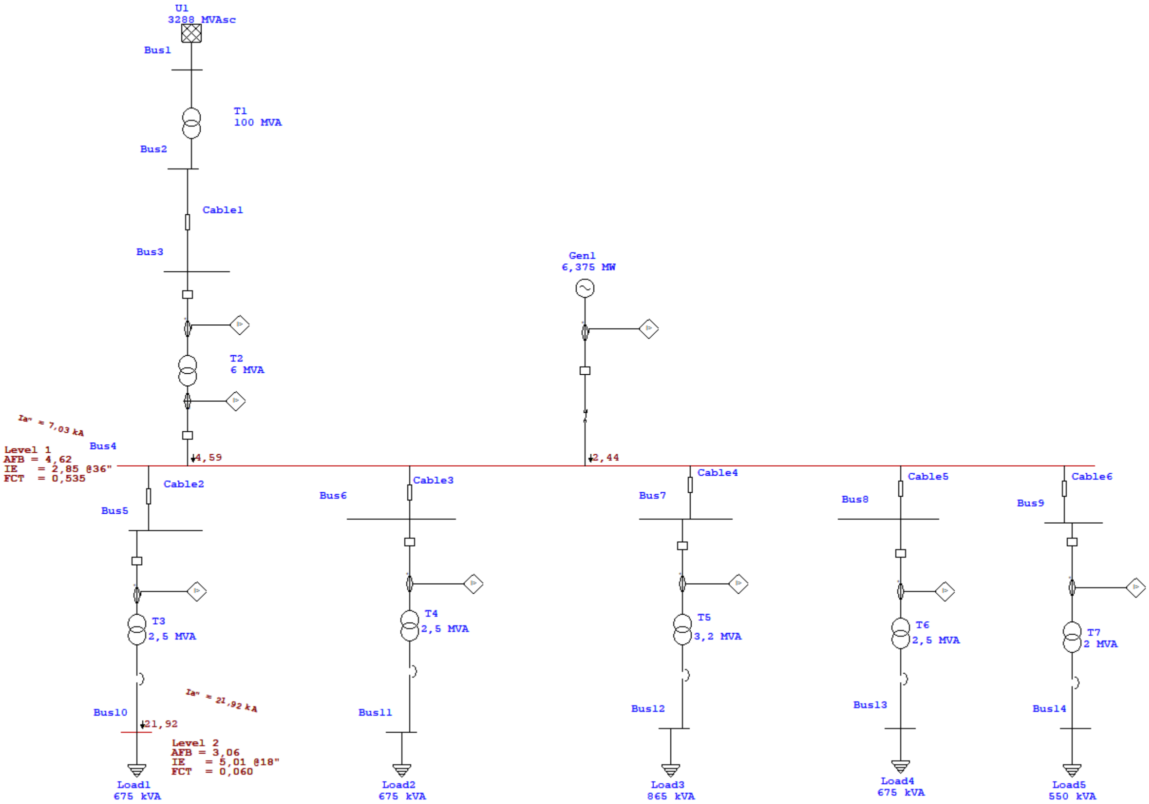


Figure 6: Arc flash analyze when Bus 4 and Bus10 are faulted in scenario 2

5. CONCLUSION

In this paper, arc flash calculation methods are presented. Also, arc flash hazards prevention and reduction methods are explained. Additionally, arc flash analyses are simulated on sample system according to different operational scenario with ETAP. After that, results have been compared in varied locations according to separate scenarios.

In these analyses, its observed that Generator contribution to the fault current is quite high; which can increase the short circuit current and arc fault current. As a result of these, arc flash incident energy on Bus 4 is %83 and on Bus 10 is %12 increased in scenario 2. Moreover, arc flash boundary on Bus 4 %35 and on Bus 10 %5 increased as well.

As explained in the paper, arc flash hazard analysis is quite important, therefore correct calculation method should be used, related measures should be taken accordingly. Because, arc flash faults have significant effect on personnel and equipment. It's really important for stability, energy continuity, human life and economy.

6. FUTURE WORK

As a future work, new analyses according to various fault types, fault locations and operation modes are planned with solution suggestions.

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