Optimization and fault diagnosis of 132 kV substation low-voltage system using electrical transient analyzer program

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ABSTRACT

In this paper, a simulation and analysis of 132 kV Substation in feeds western Iraq have been presented including a short circuit (S.C) analysis. This work helps to properly control and coordinate the protection equipment used in this grid interconnection spot. This work includes power flow analysis carried out using electrical transient analyzer program (ETAP) simulator. Also, the most common types of faults are investigated for the substation buses using International Electrotechnical Commission (IEC) and the American National Standards Institute (ANSI) standards to discover the behavioral characteristics under different scenarios for the substation transformers connection to assess the range of S.C current this substitution can ride through. Finally, the results of ANSI and IEC are theoretically investigated for validity to ensure reliability and quality assurance in the case study substation.

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1. INTRODUCTION

The main load flow studies focus on how to find the voltages and their angles at the connected buses which operate in a steady state. It is important since the bus magnitudes and voltages are needed to be specified limits [1]. The bus voltages and angles can be computed by observing and analyzing the load flow. Therefore, the reactive and real powers that flow through the power line are computed. Also, The losses can be assessed depending on comparing the power flow in sending and receiving terminals of the system [2]–[5]. The fault in the power network is a problematic failure that causes abnormal conditions leading to technical failure in the operating equipment. Generally, two failure types occur, the first is the insulation failure resulting in a line-to-line or line-to-neutral short circuit, which occurs due to degradation and overstressing on the insulator for a long time or immediately by surge overvoltage. The second failure leading to stopping the current flow is called open circuit fault. A short circuit fault leads to many problems such as thermal stress, electromagnetic interference, and lack of stability [6].

Short circuits can be a line to earth (L-E), a line-to-line (L-L), two-line to earth, and three lines to earth. The three-line fault is symmetrically affecting three phases of the system. Therefore, it is a balanced fault unlike other faults [7]. Short circuit analysis has been implemented to guarantee public safety and determine the ratings for the protection equipment and retain the stability in the power system. The maximum short circuit current (S.C) determines the minimum device ratings, whereas, a minimum short circuit current is required in relay coordination to avoid nuisance trips occurring and load deviations [8]. S.C analysis is used in overcurrent relays coordination of the radial system which is investigated using electrical transient analyzer program (ETAP) simulation and manual calculation. In [9] the results are compared using International Electrotechnical Commission (IEC) and the American National Standards Institute (ANSI) techniques. In [10], the IEEE 14-bus system is analyzed for short circuit current maximum and minimum currents. ETAP software calculates the max and min short circuit current currents for line-ground and three-phase faults on IEEE 14-bus system different buses [11].

In this paper, the short circuit characteristic of 132/33/11 kV substation in Ramadi city has been simulated and analyzed for various fault conditions at different fault locations using IEC and ANSI standards in ETAP. Detailed descriptions of S.C currents calculations are presented in this paper [12], [13].

2. SHORT CIRCUIT CALCULATIONS BY IEC STANDARDS

In IEC S.C calculation method, at the fault point voltage sources are replaced with an equivalent value. The voltage factor *c* adjusts this value for maximum and minimum current calculation. Any connected machines are represented by their internal impedance. While the transformer tap is at an operating nominal position [14], [15]. The connected impedances can be assumed at a balanced three phases hence applying symmetrical components for unbalanced fault calculations (line-to-ground (L-G) and line-to-ground (L-L-G)). Also, other components of transmission lines such as zero sequence capacitances, and parallel admittances are necessary to be under consideration in the calculations of unbalanced fault. Therefore, based on IEC 60909-0, the static load capacitances and branches are considered. Also, the analysis considers the fault point distance to the synchronous generator. Far-from generator fault (FF) calculations assume the S.C steady-state value is equal to initial symmetrical S.C yet the DC component fates to zero while near-generator fault calculations show a decaying in both DC and AC components [16]–[18].

In this paper, IEC 60,909 is being employed to study the short circuit performance of 132/33/11 kV substations. Initial symmetrical S.C (I_k'') is modeled and calculated by using nominal voltage Vn, voltage factor (C), and equivalent impedance at Z_k the fault location. Also, peak current (I_p) is tested by using I_k'' and a function of the system $\frac{R}{X}$ value at fault location k [19]–[22].

$$I_k'' = \frac{CVn}{\sqrt{3Z_k}} \tag{1}$$

$$I_p = \sqrt{2}kI_k'' \tag{2}$$

IEC Standard provides three methods to find the k factor For FF fault, the symmetrical breaking S.C. current (I_b) is equal to I_k''.

$$I_b = I_k'' \tag{3}$$

Regarding near to generator (N) fault, I_b is found by combining the contributions from connected machines. Thus, I_b for different machines can be calculated using the (4) and (5) formulas:

$$I_b = \mu\, I_k'' \tag{4}$$

$$I_b = \mu\, q\, I_k'' \tag{5}$$

where μ and q are factors for AC decay. The Steady-state S.C. I_k for each synchronous generator can be found using (6) and (7) formulas:

$$I_{kmax} = \lambda_{max}\ I_{rG} \tag{6}$$

$$I_{kmin} = \lambda_{min}\ I_{rG} \tag{7}$$

where λ is the function of excitation voltage for each generator, it is the ratio between its (I_k'') and rated current, and I_{rG} is the rated current for the generator [23].

2.1. Module analysis using ETAP

electrical transient analyzer program (ETAP) is an S.C analysis tool to explain IEC and ANSI S.C currents. It provides an editing study case to change the calculation options and criteria and build various scenarios for faulted un-faulted busses [24]. Thun, S.C runs after to customize fault currents. The targeted substation circuit components are represented in ETAP as follows: power grid is connected to bus 1 is swing (slack) with ratings of 132 kV. Cables in ETAP have a graphical representation in the edit mode [25]. All busses and lines impedances are presented per unit (PU) then they can be reverted to their Ohms actual values to be set in the ETAP Impedance tab to be taken as a typical value for the system buses [26]. There are 7 buses in the substation classified into three voltage levels. The first bus is 132 kV, buses 2, 3, and 4 are 33 kV, and 5, 6, and 7 are 11 kV. As mentioned above this software can trigger S.C mode to create a bus fault [27]. Additionally, two types of transformers can be simulated in the edit mode in ETAP which are three winding and two winding transformers. The tested 132 kV substation contains three winding transformers and three two winding auxiliary transformers. Also, there are lumped load actual values so inserted directly to ETAP [28].

3. RESULT AND DISCUSSION

According to data provided by the Ministry of Electricity, Anbar Power Network. In Table 1, the transformers' data and performance are given. The power grid and load data are simulated in a single-line diagram. System base values used in the calculations are 50 MVA and 50 Hz [29], [30]. While Table 2 illustrates all load feeders' ratings connected to the substation. The PU values are converted to the actual value to be set in related ETAP elements in the single-line diagram [31].

Table 1. Transformer's data and ratings

Transformer	Voltage (kV)	Impedance (Z)		Connection	Capacity (MVA)
1, 2, and 3	132/33/11	HV-MV	12.47%	Star-star-delta	63/50/25
		HV-LV	19.32%		
		MV-LV	9.45%		
4, 5 and 6	11/0.38	4%		Star-delta	0.25

Table 2. Load data of the main loaded feeders

Bus	Feeder number	MVA	A
2	1, 2, and 3	14.289	250
3	4	14.289	250
	5	17.147	300
4	6	22.863	400
	7	20.005	350
5	8	3.811	200
	9	4.763	250
	11	5.716	300
6	12, 13, and 14	4.763	250
7	18, 22, and 23	4.763	250
8	Station feeder	0.0724	110

This paper describes the actual values of all the data in the entire diagram shown in Figure 1, which connects the 23 feeders power grid, 3 capacitor banks, 7 buses, 3 auxiliary transformers, and 3 main transformers. The results investigate the effect of various transformer connections on different substation faults [32]. Four different connections cases for the transformers are tested as follows: Case 1: all transformers are in service, Case 2: T1 (Transformer 1) is out of service, Case 3: T2 (Transformer 2) is out of service, and Case 4: T3 (Transformer 2) is out of service. Figure 2 illustrates the procedure of analysis for this study. Every case contains two scenarios selected to investigate the effect of different connections to the transformer on the substation S.C level as shown in Table 3.

3.1. Substation load flow studies

The tested substation load flow analysis is carried out using ETAP program which applies different numerical methods [33]. After performing load flow analysis, it indicates that transformers for all scenarios are overloaded, so they must be reduced load as shown in Table 4. It is obvious the highest load in S1. Hence, analysis of load flow and S.C will be done as in Table 4.

Some 11 and 33 kV buses are operated at critical ratings of optimal power flow. Therefore, it is important to increase the capacitor bank capacity. Therefore, the total losses in parallel operations of the transformer are reduced [34]. In this work, Scenario 1 (S1) shows the maximum total losses due to handling the highest load among other scenarios, as shown in Table 5.

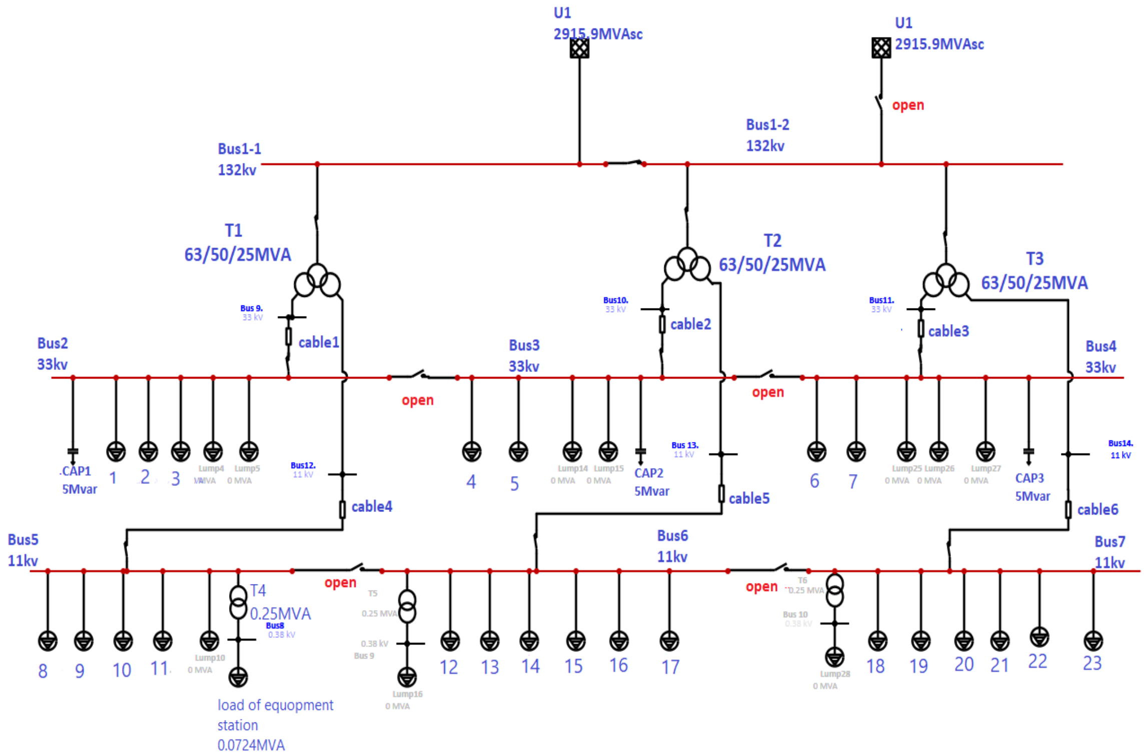

Figure 1. Single line substation diagram in ETAP

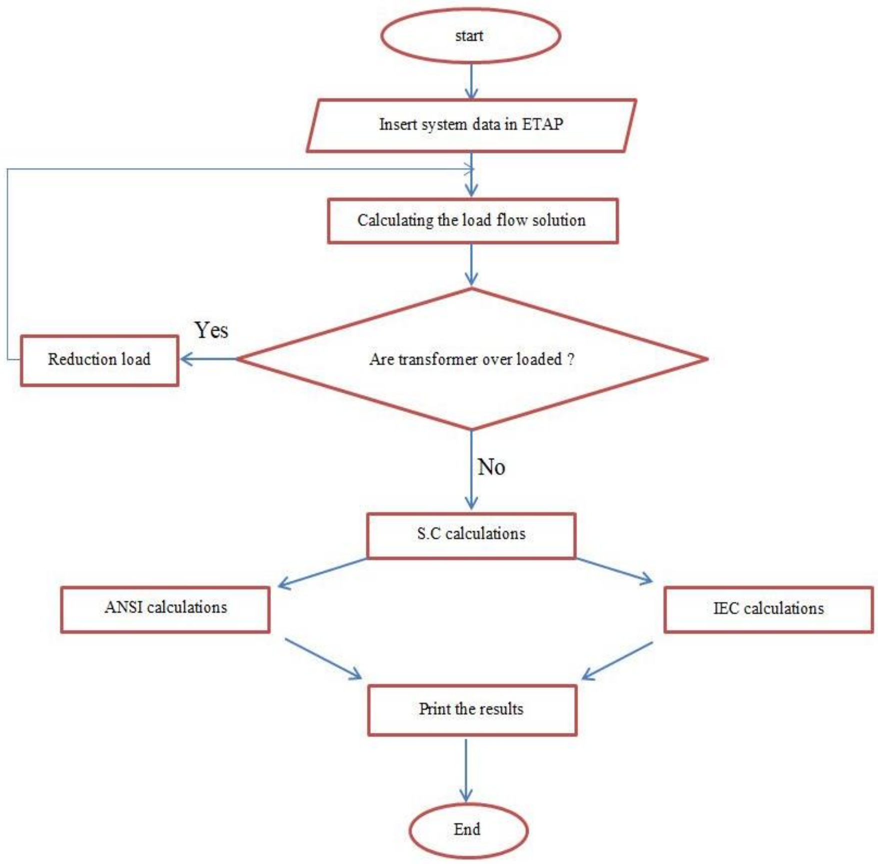

Figure 2. Flow chart for calculating load flow and S.C

Table 3. Different scenarios for main transformers

Scenario	Condition
1st Scenario (S1)	Three transformers connected in parallel
2nd Scenario (S2)	Three transformers connected in individual
3rd Scenario (S3)	T2&T3 connected in parallel
4th Scenario (S4)	T2&T3 connected in individual
5th Scenario (S5)	T1&T3 connected in parallel
6th Scenario (S6)	T1&T3 connected in individual
7th Scenario (S7)	T1&T2 connected in parallel
8th Scenario (S8)	T1&T2 connected in individual

Table 4. Reduction of loads after performing load flow

Scenario	Condition	Out-of-service feeder
1st Scenario (S1)	Three transformers connected in parallel	11, 17, 23
2nd Scenario (S2)	Three transformers connected in individual	11, 17, 22, 23
3rd Scenario (S3)	T2&T3 connected in parallel	3, 10, 11, 14, 15, 16, 17, 20, 21, 22, 23
4th Scenario (S4)	T2&T3 connected in individual	3, 5, 10, 11, 14, 15, 16, 17, 21, 22, 23
5th Scenario (S5)	T1&T3 connected in parallel	Same S3
6th Scenario (S6)	T1&T3 connected in individual	Same S4 (loads T2 feed from T1)
7th Scenario (S7)	T1&T2 connected in parallel	Same S3
8th Scenario (S8)	T1&T2 connected in individual	3, 5, 14, 15, 16, 17, 20, 21, 22, 23

Table 5. Total losses for all cases

Scenario	Total losses	
	Mw	Mvar
Scenario 1 (S1)	5.483	20.357
Scenario 2 (S2)	5.154	19.148
Scenario 3 (S3)	3.629	14.825
Scenario 4 (S4)	3.078	11.958
Scenario 5 (S5)	3.626	14.822
Scenario 6 (S6)	3.076	11.955
Scenario 7 (S7)	3.623	14.819
Scenario 8 (S8)	3.333	13.796

3.2. Ramadi 132 kV substation S.C analysis

In this paper, the analysis is according to IEC and ANSI models. In the targeted substation, all transformers are operating individually. In this work, transformers are connected in parallel as shown in Table 6 to investigate the influence of this connection on S.C analysis and evaluation. There are four types of faults are used in this study: 3-ph fault; Line -Ground (L-G); L-L-G; and L-L; at operating buses [35].

3.3. Simulated results for ANSI calculations

At faulted buses, the calculation of S.C used 1.5-4 cycles to perform 3-ph, L-L-G, L-L, and L-G faults according to ANSI to determine the S.C currents RMS value. The results of the actual operation are depicted in Table 6. Parallel transformer scenarios demonstrate the highest S.C increase, while the individual connections scenario showed a shallow S.C current increase. Thus, buses 2 and 3 have more S.C percentage increase than bus 1. The decrease in operating voltage causes increasing in S.C readings. Consequently, the first scenario has S.C currents increase.

In Table 6 all fault types are examined, the highest S.C occurred at buses 1, 4 and 6. There is no pattern for the assigned faults since each bus shows a different response. All scenarios' results are compared with the second scenario to evaluate the buses' S.C response for all proposed transformers. All faults proposed on buses (1, 2, and 3) are examined as presented in Figures 3(a) to 3(c).

3.4. Results for IEC calculations

The IEC standard results are different from than ANSI standard regarding the different scenarios. The initial symmetrical currents (I_k''), breaking current (I_b), steady-state S.C (I_k), and peak S.C (Ip) are analyzed. As we noted in (1) to (7) formulas, the model is set to test maximum S.C. The modeling S.C to evaluate the performance of the system with different short circuit transformer connections. The minimum S.C.C is tested to be used for protective equipment. The L-G, L-L, L-L-G, and 3-ph (per IEC 60909 Standard) faults are modeled [36]. All fault types are tested on the buses (1-3). Figure 4(a) to 4(c) presents the results of different scenarios; each scenario has parallel transformers connection demonstrated a high S.C increase. The individual connections showed less increase in S.C currents. Thus, buses 2 and 3 have more S.C percentage increase than bus 1. The decrease in operating voltage causes increasing in S.C readings. Consequently, the first scenario has S.C currents increase. IEC showed better response than ANSI.

Table 6. ANSI 2nd scenario results

Bus		Fault types KA			
Bus ID	kV	3-Ph	L-G	L-L	L-L-G
Bus 1	132	14.636	10.174	12.920	13.684
Bus 2	33	10.842	12.792	10.037	12.192
Bus 3	33	10.534	12.438	9.695	11.595
Bus 4	33	11.029	12.937	10.229	12.065
Bus 5	11	20.394	0.956	18.613	18.682
Bus 6	11	21.465	0.977	19.795	19.795
Bus 7	11	21.177	0.97	19.455	19.455

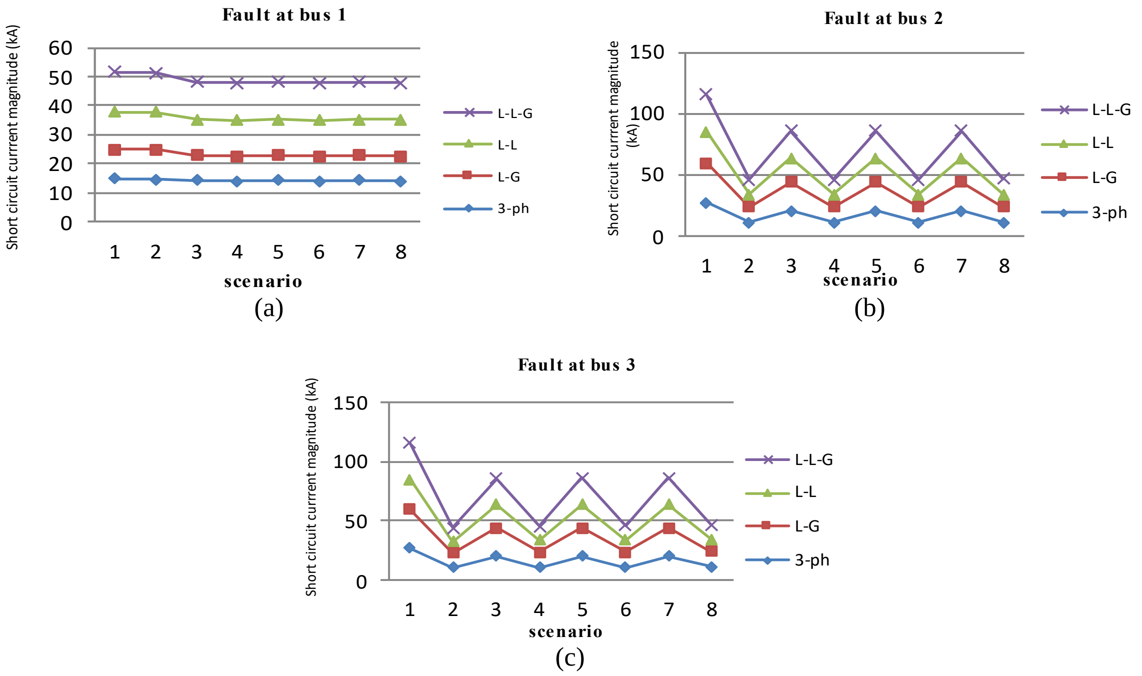

Figure 3. The scenarios on bus 1-3 for ANSI calculations for (a) 1st bus, (b) 2nd bus, and (c) 3rd bus

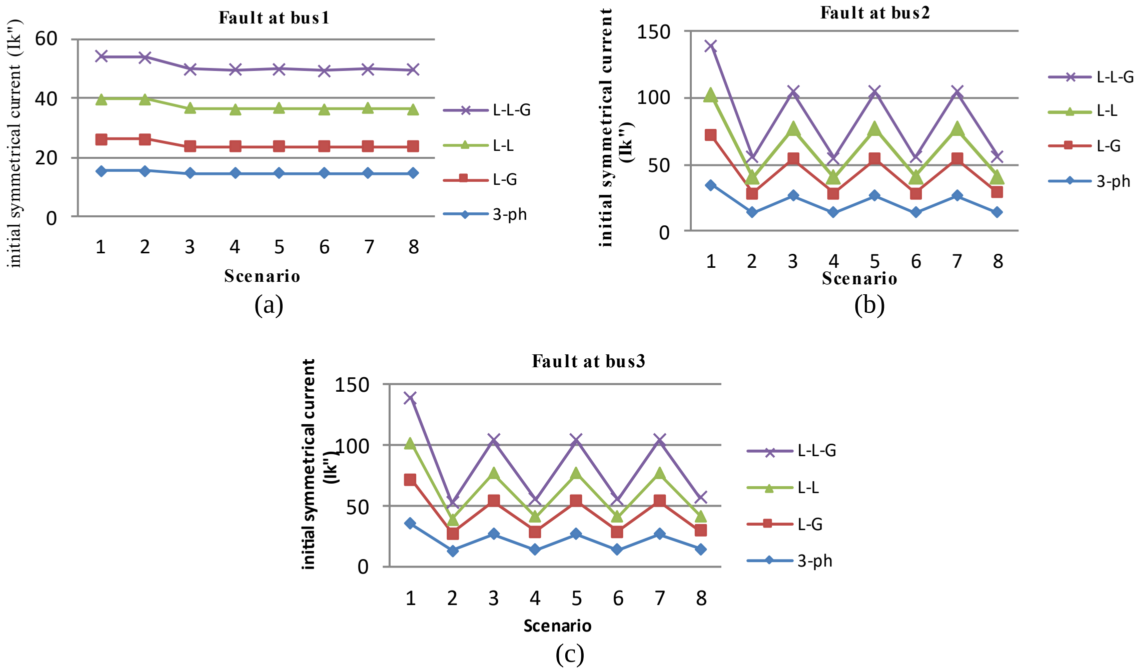

Figure 4. S.C for all fault types and scenarios (a) 1st bus, (b) 2nd bus, and (c) 3rd bus

4. CONCLUSION

In this work, the single-line diagram of the tested substation is simulated using ETAP. Evaluation and investigation of power flow and S.C profile are performed. The system connects the 23 feeders power grid, 3 capacitor banks, 7 buses, 3 auxiliary transformers, and 3 main transformers. The results investigate the effect of various transformer connections on different substation faults. The analysis concludes the following: i) according to the load flow analysis on operating company data, the transformers for all selected scenarios are overloaded, so a load shedding program must be applied; ii) uses at 33 and 11 kV operate at the critical voltage ratings for optimal power flow. Therefore, the capacity of the capacitor bank must be increased; iii) no general pattern of the simulated results is noted for fault types; iv) the transformer connection has direct effect on the system response, where parallel connection gives max S.C current and could increase the load capacity; and v) IEC and ANSI demonstrate different results for same scenarios. The IEC technique findings are greater than ANSI due to the impedance correction and voltage factor which are taken into account in IEC standard which means that IEC is better and safer than ANSI standard.

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