A Proposed Underground Medium Voltage Feeder-Design Considering Ampacity and Temperature of Cable for High Rise Buildings in Pakistan

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Abstract

A common aspect of modern power distribution systems (MPDS) is the substantial use of underground power cables (UPC) due to space scarcity, human safety, and aesthetic reasons. These insulated UPC are either directly buried in the ground or laid in conduits or concrete ducts. Selecting cable of a suitable ampacity for catering anticipated load, under expected operating temperature and thermal resistivity of soil is a challenging problem. In this paper, a new UPC design is proposed for high-rise buildings (HRB) in the G-13 Sector of Islamabad, Pakistan. After power flow analysis of the selected HRB's load for estimation of cable size, the number of UPC feeders of adequate ampacity are decided for delivering power to the selected HRBs. Furthermore, steady-state temperature analysis is performed on the directly buried UPC feeders for the analysis of temperature effects around the cables. The MPDS, as well as the HRB's load, are modeled in Electrical Transient Analyzer Program (ETAP) according to IEC and IEEE standards. Simulation results indicate that the designed system can also handle 20% additional future load to accommodate the government policy of promoting electric vehicles.

Keywords: *Ampacity; Buried Cables; Cable Thermal Capacity; Derating Factor; ETAP.*

1. Introduction

With the fast-rise construction of HRB's and residential complexes in metropolitan areas, there is no space and human safety in the overhead distribution system. Therefore, the underground distribution system is more suitable in residential areas. In contrast, installing the underground cables requires some specification for the ampacity and temperature around the cables.

The intended cable ampacity is essential when designing an underground distribution system. The cable's capacity to disperse the heat generated in the conductor is determined by the cable insulation's effective conductivity and the surrounding environment. However, the most affected parameters in the environment are ambient temperature and soil thermal resistivity. Hence, heat dissipation was one of the limiting factors that had the most significant impact on ampacity. In addition, the working temperature for the specific cable set-up and installation rises as the running load current increases, which might result in quick cable damage or failure.

The primary means of transmitting electrical energy is through the power cable. However, long-distance cable-based power transmission and distribution capacity is frequently derated [1]. So, to avoid failures, particularly in situations when the serviceability of the installed cable is challenging, the derating factor is critical for calculating the safe operation for all worst-case scenarios along the feeder. Due to the pessimistic approach, the derated ampacity will remain significantly less than the actual highest current-carrying ability in most circumstances. However, in other circumstances, by including the requirements under standards, essential information of ambient circumstances and projecting methodologies are employed to exploit that additional ampacity. For this purpose, the IEC standard was divided into many sections, as indicated in [2-7]. For underground buried cables, IEEE standard 835-1994 [8] produces results equivalent to IEC standards. At the same time, the Neher-McGrath approach is used in both IEEE and IEC standards [9]. The IEC standard is complete because the technique is more up-to-date. Similarly, excluding a few variations in style for cable in the air, the IEEE and IEC criteria are essentially identical in numerous characteristics involving belowground cable computations [10]. The different derating factors on buried cable in-ground and the current-carrying ability affected these factors. These are the factors that primarily affect the cable's ampacity: the type of conductor (Al), the thermal resistivity of the native soil, the depth of laying, the surrounding temperature, the cable size, and grouping factors. As a result of the above, this study will examine the ampacity and steady-state temperature

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of medium voltage underground cables established using various environmental conditions in Islamabad, Pakistan.

In this paper, the ampacity and temperature of the underground cable are designed to consider different derating factors in ETAP software. Furthermore, the power flow and steady-state temperature analysis are performed on underground medium voltage cables for the HRBs load. The single-core XLPE 11KV 240mm2 cable is considered. Although the effect of numerous parameters on the cable temperature and the ampacity of directly buried in the ground in flat and trefoil installation method, the external environmental effects were investigated in this research.

The remaining paper was laid out in the following manner, section 2 explains UPC design properties and environmental conditions, in section 3 ampacity derating factors are discussed, furthermore, the methodology of this proposed method is discussed in section 4, the result and discussion are elaborated in section 5, and section 6 conclude this paper.

2. UPC design properties and environmental conditions

The ETAP software requires cable components for modeling. The cable characteristics below are derived from the Olex HV cable Catalogue [11]. As a reference, an XLPE insulated cable (11kV), 240mm2 AL conductor often used in practice is recommended. Table 1 shows the essential required components of the cable and environmental parameters. Fig. 1 shows different insulation layers components of the cable, which are required to model the system in ETAP.

Table 1: UPC Design parameters and installation conditions

Sr. No.	Parameters	Values
1	Voltage of operation	11 KV
2	Frequency	50 Hz
3	Conductor Size	240 mm^2
4	Type of conductor	Aluminum
5	Max. temp. of cond. For XLPE	90° C
6	Insulation	XPLE
7	Loading Factor	1
8	Duct type	Directed buried
9	Depth of burial of cable	0.8 m
10	Ambient temperature	25° C
11	Thermal resistivity of soil	1.1 K.m/W

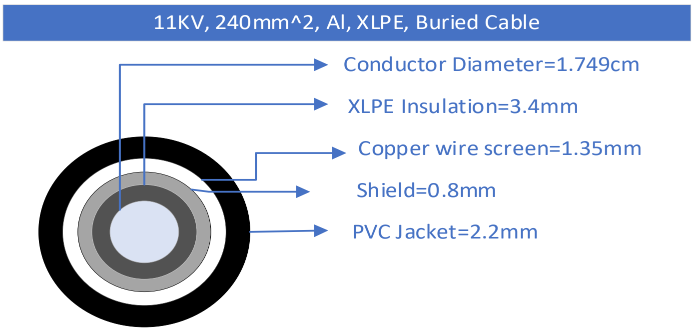

Fig.1: Cable cross-sectional area

3. Ampacity derating factors

These are some factors [12] under consideration in this paper, which are given below. After applying multiple correction factors to the maximum allowable current, depending on the type of installation and conductor size. The maximum allowable current of the cable decrease when applying the derating factor of the ambient temperature, native soil thermal resistivity, installation depth, and the number of nearby circuits.

$$I = I_0.F_{ta}.F_{dep}.F_{cir}.F_{soil}.F_{dist} \tag{1}$$

Whereas,
I_0 = based on the type of installation and conductor size, the maximum allowable current (A),

F_{ta}= the soil temperature correction factor
F_{soil} = correction factor due to the soil resistivity around the cable.
F_{dep} = The adjustment factor is due to cable installation depth.
F_{cir} = According to the number of neighboring circuits correction factors.
F_{dist}= correction factor for the distance between the circuit.

3.1. Thermal resistivity of the soil

The soil resistivity is a characteristic that works in tandem with the ambient temperature. The cable ampacity is heavily influencing though the surrounding medium's conduction capacity in the direct laying-in ground environment. Mostly the thermal resistivity is assumed for the cable current-carrying capacity; such suppositions in the worst-case scenario could not maintain the permitted current within acceptable limit. The heat resistivity of the soil in the fixed location is not uniform, even though homogeneous soil is commonly presumed [7]. It was heavily reliant on moisture movement. The damp soil's thermal resistance is homogeneous. The homogeneity assumption does not hold when the damp soil surrounding the cables is heated up by cable temperature dissipation, causing the soil to dry up around the cable. Thermal resistivity is the reciprocal of thermal conductivity, the area where thermal conductivity is less than the current-carrying capacity of the cable decrease.

3.2. Depth of burial cable

The cable's current carrying capacity decrease as the depth of burial increase. The needed cable depth of burial is determined by the following factors: the purposed circumstance or code constraint, the cable working voltage, cable type, and whether the cable is directly laid in the ground or laid in channels or tangible canals.

3.3. Local soil ambient temperature

The temperature of the soil is different for different locations of the placement. Many cable ampacity application tables are based on a standard soil ambient temperature of 20° Celsius (68° Fahrenheit), which may not be acceptable for warmer or colder areas.

$$I = I_0 * \sqrt{\frac{(t_c - t_b)}{(t_c - t_d)}} \tag{2}$$

I =Ampacity has been adjusted to account for the new ambient temperature (Amperes)
I_0 =maximum ampacity of the cable according to the standard in ampere.
t_c =The temperature of the conductor for which ampacity is computed (°C)
t_d =The temperature of the environment for which ampacity is estimated (°C)
t_b = °C new ambient temperature

3.4. Temperature limits for cables

Medium-voltage cables have continuous maximum working temperatures of 90 or 105 degrees Celsius. Many cables also include a temperature rating for emergency overload.

4. Methodology

There are two primary phases in the approach. Initially, load data for a high-rise structure (Federal Govt Housing Authority Tower) located at G-13 Islamabad was obtained by extensive practical surveys. After that, ETAP was utilized to simulate and evaluate load flow analysis and steady-state temperature study of UPC. The load for an HRBs is designed on ETAP then load flow analysis is performed for the appropriate size of the cable carrying the desired load current is chosen. After all the critical load data and desired number of feeders to go thermal analysis of UPC to optimize cable performance under different factors that affect current-carrying capacity. In this paper, the two cases of the directly buried cable are discus, one is flat installation formation, and the other is trefoils installation formation. IEC-60287 method is used for steady-state temperature analysis of the UPC.

4.1. ETAP software

ETAP is the most comprehensive analysis platform for generation, transmission, distribution, industrial power systems design, simulation, operation, control, optimization, and automation. The ETAP enterprise solution takes to design and analysis innovation to a new degree of sophistication, laying the groundwork. ETAP19.0.1 is planned to fulfill all the industry's criteria in every way. The ETAP suite now includes additional vital analytical modules and time-saving possibilities. These include Arc flash, load flow analysis, short circuit, relay coordination, cable capacity, transient stability, and optimum power flow [13]. Its modular functionality may be customized to meet the demands of any business, from remote power systems to massive power systems. Specific information for all equipment (generator, transformer, and shunt equipment) is readily available, saving the user time ETAP gave an error report to the user, highlighting the fault in a concise summary.

4.2. HRBs load profile

Extensive practical surveys were conducted to collect the needed load data for these locations. The Federal Government Housing Authority Tower, located in the G-13 Mauve area in Islamabad, is a 25-story HRBs that spans about 3.3 million square feet. It is divided into three-tower/Blocks (1, 2, and 3) and contains 1467 apartments with two and three bedrooms. It also features 16 elevators that can transport both people and freight. Table 2 shows the load statistics for the block (1, 2&3).

Table 2: Ultimate total load of Block-1,2,3

Sr. No.	Parameter	Value
1	Ultimate total load of Block-1 (kW)	4152.12
2	Ultimate total load of Block-2 (kW)	4535.22
3	Ultimate total load of Block-3 (kW)	4122.07
4	Ultimate total load of Block-1,2 & 3 (kW)	12809.41
5	Ultimate total load (MVA)	15.07

The ultimate load demand with a 100% load factor is 15.07 MVA. Table 2 contains the total load of the desired HRBs, so, to design the medium voltage distribution system that supplies the continuous power supply. Furthermore, these HRBs contain large parking spaces, so, in the next few years, the government of the Pakistan policy is to replace the oil combustion vehicles with Electric vehicles. For this purpose, in this paper, we design a UPC system that supplies the power to an additional 20% load of the HRBs calculated load. There are three types of EV chargers available in the market: Type 1, type 2, and type 3. Type 1 and 2 are used for residential and commercial purposes; the charging time for type 1 is more than 12 hours, whereas, for type 2, the charging time is 6-8 hours. Type 3 is a fast DC charger its charging time is 0.5-1 hour.

4.3. IEC-60287 Method

The electrical analogy is transformed to a thermal analogy, representing the thermal-electrical equivalent circuit; according to the IEC 60287 standard, capacitances do not affect steady-state computations. However, the electric current conduction in electric networks is analogous to heat transfer through conduction. So, the allowable current of buried AC cable when the soil does not dry out or AC cable in the air may be computed using an equation based on IEC 60287.

$$I = \sqrt{\frac{\Delta\emptyset - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nr(1 + \lambda_1)T_2 + nR(1 + \lambda_1 + \lambda_2)(T_3 + T_4)}} \tag{3}$$

Where W_d (W/m) is the dielectric loss measured per unit length of cable insulation, where $\Delta\emptyset$ (^{0}C) is the temperature difference between ambient and maximum allowed conductor temperature. In contrast, the thermal resistances T1, T2, T3, and T4 (0K.m/W) are thermal resistances. Furthermore, the AC resistance R(Ω/m) is the cable's operational resistance and is a function of temperature and frequency, and n is the cable's number of conductors. The loss factors are also the proportions of total losses in metallic sheath to total conductor losses in cables.

The Neher-McGrath technique and the IEC method for calculating cable ampacity are nearly identical in theory, except that the latter incorporates additional breakthroughs since the Neher-McGrath procedure was created. Therefore, this composes the IEC extra complete because the technique is more up to date. In consequence, excluding for a few variations in style for cable in the air, the IEEE and IEC criteria are in essence identical in numerous characteristics involving belowground cable computations [14].

5. Result and discussion

The ampacity performance analysis of directly buried aluminum Conductor cable 3-1/c,240mm^2 with derating factors is discussed in this section. In addition, the derated ampacity is also analyzed in this section. Furthermore, for the system stabilization, the power flow analysis was performed on the HRBs. The steady-state temperature analysis is performed in the ETAP for the temperature analysis of the UPC.

5.1. The ampacity of the UPC under derating factors

The ampacity of the UPC is mainly affected by some derating factors discussed in detail. The soil thermal resistivity was performed using varying resistivity values for the above-stated cable. This analysis was performed using the conditions stated above. The finding suggests that the derating caused by a tiny factor change in soil resistivity is more significant than that caused by a change in ambient temperature. The assessment of the current-carrying capability with the soil resistivity is shown in Fig. 2. In the proposed case, the ampacity decreases as the thermal resistivity increases. The soil thermal resistivity is 1.1 K-m/W, and the current carrying capacity of the cable is 340A.
Furthermore, the observations have been performed on cables buried directly in the ground. The depth of interment is another relevant issue to consider in calculating ampacity. In the standard case, the ampacity is given at a depth of 0.8m. Whenever the laying depth of the cable is increased, the ampacity is reduced and vice versa, as illustrated in Fig. 3. In the examined case, the depth of the laying is 0.8 m, and the current carrying capacity of the cable is 367A.

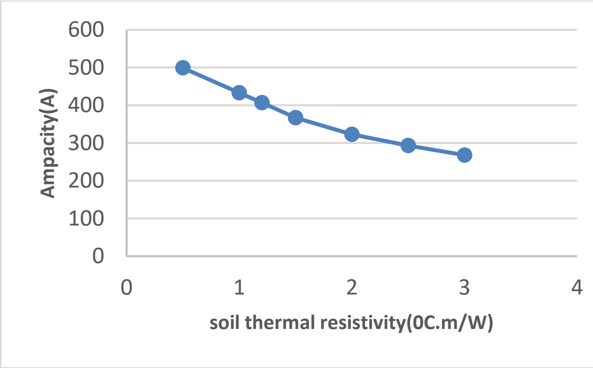

Fig. 2: Soil thermal resistivity vs Ampacity

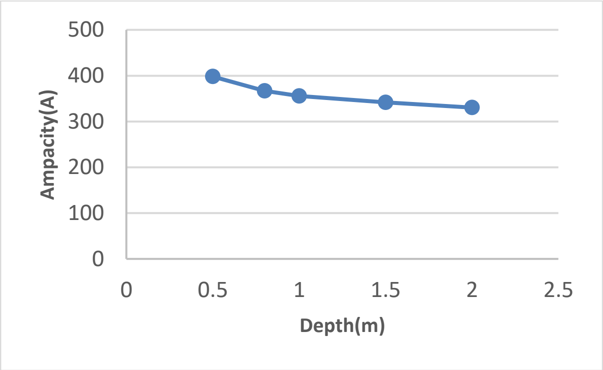

Fig. 3: Cable depth vs Ampacity

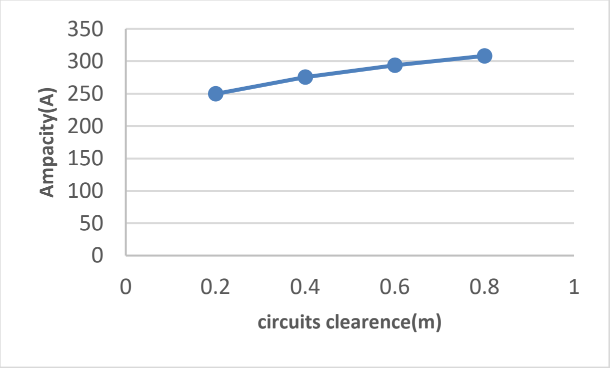

Fig. 4: In grouping circuit clearance vs Ampacity

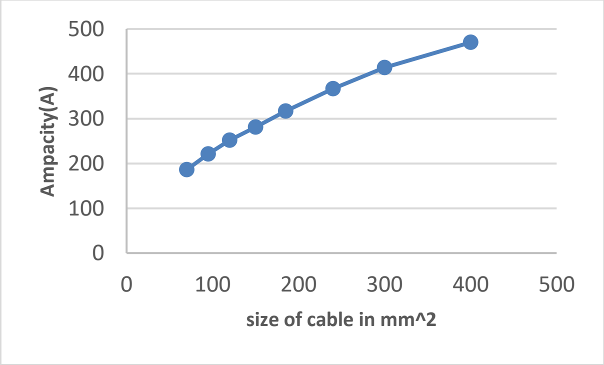

Fig. 5: Cable size vs Ampacity

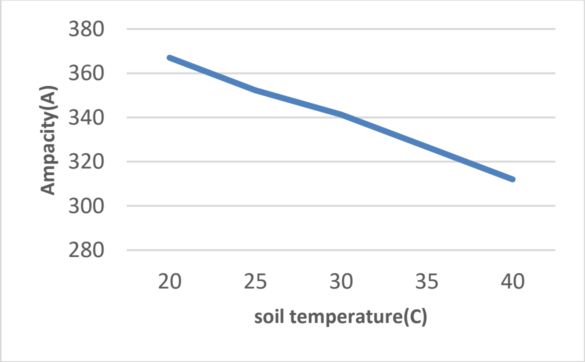

Fig. 6: Soil ambient temperature vs Ampacity

The conductor size was varied for a wide range from 70 to 400 mm^2. Cables are placed and spaced in a trefoil pattern indirectly buried underground system. The current carrying capacity of aluminum conductors of different sizes is given below. The ampacity (or current-carrying capacity) of a conductor rises as the size of the conductor increase, as seen in Fig. 4**.** Furthermore, as we see in Fig. 5, the ampacity reduced when the soil ambient temperature increased. As for the standard, the ambient temperature is 200C, and the ampacity according to IEC 60502 is 367A.In this case study, the ambient temperature is 25 ^{0}C, so the ampacity is reduced to 350A. When the multi-circuit is laid in the same trench, the ampacity is affected through the circuit clearance distance. So, in Fig., as the circuit-to-circuit clearance distance increase, then the ampacity of the cable increases; meanwhile, the heat dissipation of the surrounding soil is increased, and the mutual heating effect is reduced.

As observed from the ETAP simulation results, the total derated current of the feeders of flat and trefoil installation formation are 278.6A and 274.1A. Besides that, this system requires 4 feeders of the above-given size of the cables to achieve this current. Furthermore, load flow analysis and steady-state temperature analysis are performed on the system to determine the stability of the whole system, as discussed below

5.2. Power flow analysis of the HRBs

Considering all the deratings factors, the cable of flat and trefoil installation formation ampacity according to IEC-60502 is 278.6A and 274.1A. The load flow analysis result is shown in Fig. 3and Table 3. Four feeders serve the desired HRBs load, and every feeder carries 219.9 A. The total length of feeders is 2112m, and the voltage drop found is 1.38%, which is well less than the maximum voltage drop limit of 5%. From the load flow analysis presented in Table 3, we observed that every piece of equipment is working within its limit and the system is stable. Moreover, the voltage at the consumer end is also within range. After the load flow analysis, the next step is to analyze the steady-state temperature of the direct buried underground cable. In the next section, the steady-state temperature analysis is discussed.\

5.3. Steady-state temperature analysis of the UPC for desired HRB

The steady-state temperature analysis of the desired UPC system is designed in ETAP, and their analysis is performed. Furthermore, their results are given below. Two laying methods are studied in this paper, Case 1 is directly buried Flat installation formation, and case 2 is directly buried trefoil installation formation. These cases are further discussed in the details given below.

5.3.1. Case 1: Flat installation formation

In this case, directly buried flat installation formations are studied, and their steady-state temperature analysis is performed. In our case, the derated ampacity of the flat installation formation is 278.6A. Furthermore, the steady-state temperature of HRBs load is performed in Fig. 7 according to Eq. (3), in which the minimum and maximum temperatures of the cables are 61.330C and 68.340C. The result shows that this UPC system is suitable for the HRBs loads; hence all the cable's temperatures are analyzed for the desired conditions are within limits. The temperature is also in the satisfying range.

Moreover, when adding the 20% additional load for the future government of Pakistan policy related to Electric vehicles, for this purpose, we performed the load flow analysis and steady-state temperature analysis of the desired cables size for the same environmental conditions. From the load flow analysis, the load current of every feeder is 260.95A, but the derated current of the cables is 278.6A. Therefore, the system can be able to power supply these desired loads. Consequently, the steady-state temperature analysis results are shown in Fig. 8**Fig**. The minimum and maximum temperatures of the UPC system, respectively, are 79.52 0C and 90.150C. In contrast, the design system supplies the additional 20% loads within the limited temperature ranger.

There are three types of EV chargers available in the market: Type 1, type 2, and type 3. Type 1 and 2 are used for residential and commercial purposes; the charging time for type 1 is more than 12 hours, whereas, for type 2, the charging time is 6-8 hours. Type 3 is a fast DC charger its charging time is 0.5-1 hour. In the HRBs, the total number of parking spaces is 1780. Moreover, the design system can charge 600 EV of type 2 chargers.

Table 3: Load flow analysis of the HRBs

ID	KW Flow	KVar Flow	Amp Flow	% Loading	% Voltage Drop	KW Losses	KVar, losses
Cable1	3466	2353.3	219.9	78.9	1.38	47	33.39
Cable3	3466	2353.3	219.9	78.9	1.38	47	33.39
Cable4	3466	2353.3	219.9	78.9	1.38	47	33.39
Cable5	3466	2353.3	219.9	78.9	1.38	47	33.39
Cable22	4417.1	3003.6	284.3	79.7	0.01	0.372	0.264
Cable23	4397.8	2989.8	283	79.4	0.01	0.369	0.262
T30	27.9	17.67	1.757	92.4	2.08	0.419	0.645
T31	27.96	17.72	1.762	92.6	2.09	0.421	0.648
T32	195.2	131.2	12.52	90.8	3.44	2.28	11.61
T33	2165.1	1468.3	139.2	84.4	3.15	12.58	134.3
T34	110.8	72.09	7.035	83.2	2.38	1.15	4.13
T37	199.7	132.6	12.76	77.5	2.92	1.97	10.05
T38	82.39	53.68	5.234	85.6	2.45	0.879	3.17
T39	1936.9	1322.4	124.8	90.6	3.4	12.14	129.5
T40	175.3	117.8	11.24	90.6	3.43	2.04	10.4
T41	23.93	15.16	1.508	92.4	2.08	0.36	0.554
T42	19.97	12.61	1.257	77.4	1.74	0.25	0.385
T43	41.59	26.7	2.63	64.6	1.93	0.401	1.17
T45	21.82	13.8	1.374	84.4	1.9	0.299	0.46
T46	21.18	13.38	1.333	81.9	1.84	0.281	0.433
T47	162.3	108.4	10.39	84	3.17	1.74	8.89
T48	81.52	53.09	5.178	84.7	2.42	0.86	3.1
T49	195.3	129.5	12.47	75.9	2.85	1.88	9.61
T52	38.65	24.42	2.433	81.6	1.83	0.511	0.786
T56	130.3	86.83	8.331	82	3.09	1.36	6.95
T58	1936.8	1322.3	124.8	90.6	3.4	12.14	129.5
T63	41.59	26.7	2.63	64.6	1.93	0.401	1.17
T65	2165.1	1468.3	139.2	84.4	3.15	12.58	134.3
T67	1936.9	1322.4	124.8	90.6	3.4	12.14	129.5
T69	1936.8	1322.3	124.8	90.6	3.4	12.14	129.5

Fig. 7: Steady-state temperature analysis of HRBs in flat installation formation

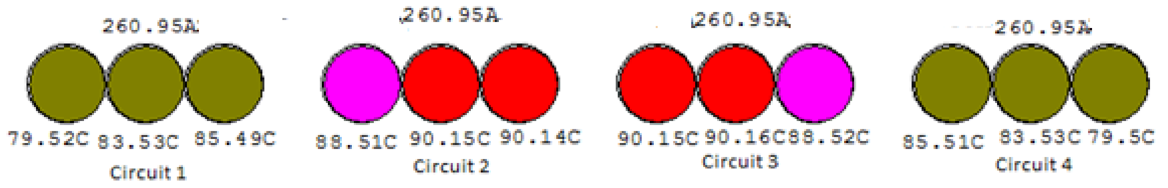

Fig. 8: Steady-state temperature analysis of HRBs in flat installation formation with 20% additional load

5.3.2. Case 2: trefoil installation formation

In this case, directly buried trefoil installation formations are studied, and their steady-state temperature analysis is performed. The derated ampacity of the trefoil installation formation is 274.1A. Furthermore, the steady-state temperature of HRBs load is performed on ETAP, and their result is shown in Fig. 9. The cable's minimum and maximum temperatures are 63.28 ^{0}C and 68.77 ^{0}C. The result shows that this UPC system is suitable for the HRBs loads. All the cable's temperatures are analyzed for the desired conditions.

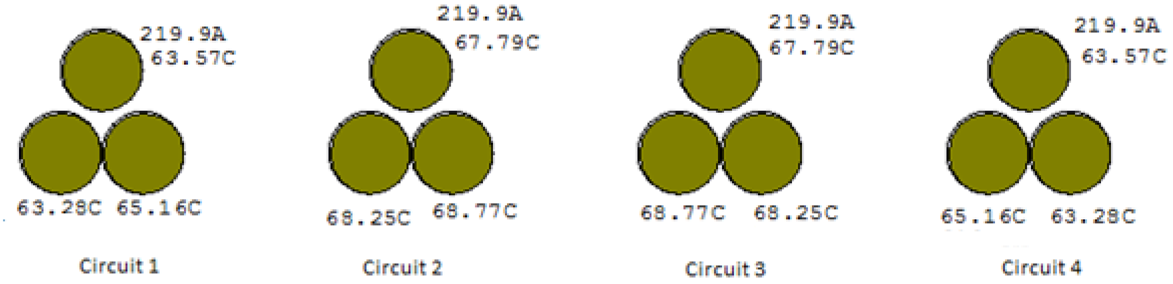

Fig. 9: Steady-state temperature analysis of HRBs in trefoil installation formation

The future government of Pakistan policy related to Electric vehicles stated that a system should handle 20% additional load on the system. So, we tested our system for 20% additional loading. For this purpose, we performed the steady-state temperature analysis of the desired cables size and followed the same environmental conditions. From the load flow analysis, the load current of every feeder is 260.95A, but the derated current of the cables is 274.1A. So, this system can power supply these desired loads.

The steady-state temperature analysis results are shown in Fig. 10. The minimum and maximum temperatures of the UPC system are 82.47^{0}C and 90.82^{0}C. There is an increase in temperature; however, the designed system supplies the 20% additional load.

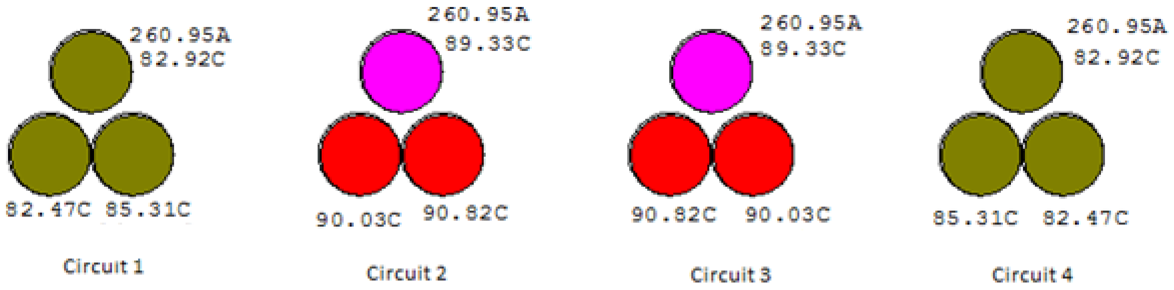

Fig. 10: Steady-state temperature analysis of HRBs in flat installation formation with 20% additional load

The above-mentioned cable parameters and environmental installation conditions are for the desired location, i.e., G-13, Islamabad, Pakistan. The HRBs load and medium voltage underground cable system are modeled in ETAP; furthermore, the load flow analysis and steady-state temperature analysis are performed to check the system stability and the thermal analysis. In this paper, two directly buried laying methods are discussed. Also, flat and trefoil installation formations are performed for this analysis. The result shows that the flat installation formation derated ampacity is greater than the trefoil installation formation.

Moreover, the steady-state temperature of the UPC system in the flat formation is less than in the trefoil installation formation. Hence, flat installation formation provides the best results for HRBs. Also, 600 EV of type 2 chargers can be fully supplied from this design system.

6. Conclusion

A convenient feature of recent power supply systems is the significant use of underground power distribution systems because of the lack of space and social protection. These isolated underground power distribution systems are also directly laid in the ground or laid in channels or tangible canals. A novel underground power distribution system scheme is proposed for HRBs in the G-13 Sector of Islamabad, Pakistan. Afterward load flow analysis of the selected HRB's load for assessment of cable sizing, the desired numbers of feeders/circuits of suitable current carrying capacity are chosen for supplying power to the designated HRBs. Furthermore, stable condition temperature investigation is executed on the directly laid-in ground feeders for the investigation of temperature effects around the cables. The underground power distribution system and the HRB's load, are modeled in Electrical Transient Analyzer Program (ETAP) according to IEC and IEEE standards. As the result shown above both cases of flat and trefoil installation formation would be able to power supply to the desired HRBs load. According to the ampacity and temperature analysis, the flat installation formation is the best laying method. Furthermore, the designed system can also be able to handle 20% additional future load to accommodate the government of Pakistan policy of promoting electric vehicles. In the future there are additional electromagnetic effects that were ignored in this research, which would result in a completely different dynamic when considering the impact of eddy currents on cable thermal characteristics in both the steady state and during a fault. Furthermore, the effect of total harmonic distortion current produced by EV on the UPC ampacity and thermal characteristic in both steady state and dynamic analysis.

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Appendix; UPC laying ways and environmental parameters

An 11kv 3-1/c, 240mm^2, Al conductor, XLPE insulation cable are modeled in ETAP for the analysis of ampacity and temperature around the cables. Fig. 1 shows the underground directly buried flat installation formation and Fig. 2 shows the trefoil installation formation. Fig. 3 shows the load flow analysis of HRBs.

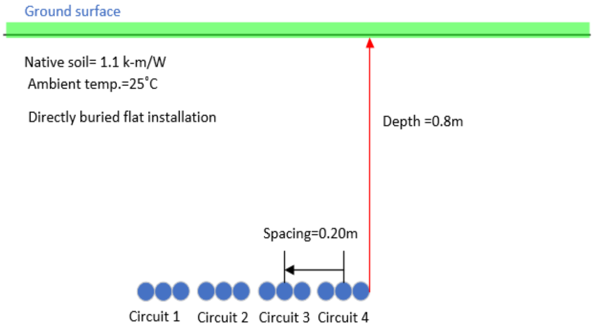

Fig. 1. Directly buried in ground flat installation formation

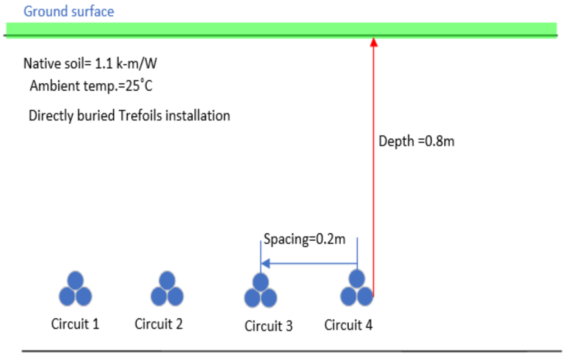

Fig. 2. Directly buried in ground trefoil installati formation

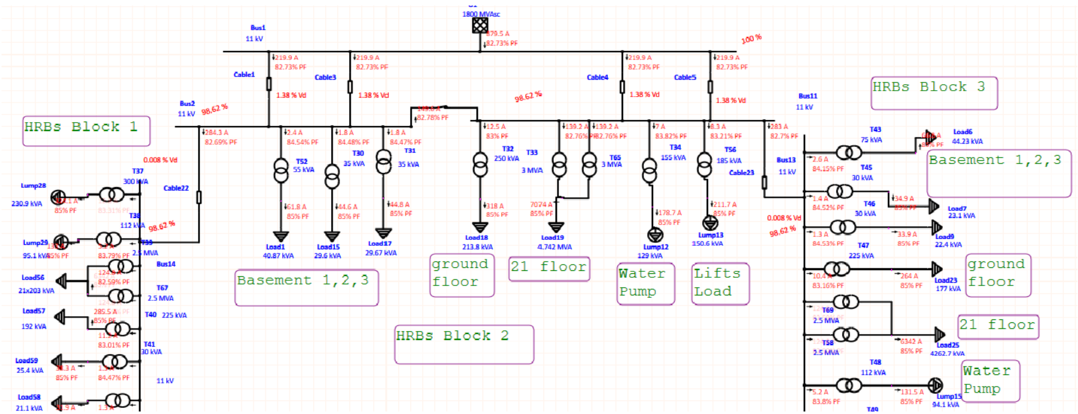

Fig. 3. Load flow analysis of HRBs