Optimization of HV cables design & material consumption

Optimización del diseño y consumo de material del cable HV
Otimização do design de cabos de alta tensão e consumo de materiais

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Abstract

This paper discusses the results of a basic study for the development of High Voltage (HV) XLPE cables. The authors have studied effects of changing basic construction of HV cables in order to improve design and material consumption of HV cables and studying these changes effect on the quality of manufactured HV cables. Studying of XLPE material's properties, such as minimum insulation breakdown stress, PD level, electric fields change and etc. to set the proper design values for HV cable designing. Electrical field study for this paper has done with ANSYS software.

Keywords: High Voltage Cable; Elctrical field; XLPE; Insulation thickne; ANSYS.

Resumen

Este documento analiza los resultados de un estudio básico para el desarrollo de cables XLPE de alto voltaje (HV). Los autores han estudiado los efectos de cambiar la construcción básica de los cables de alta tensión para mejorar el diseño y el consumo de material de los cables de alta tensión y estudiar el efecto de estos cambios en la calidad de los cables de alta tensión fabricados. El estudio de las propiedades del material XLPE, como la tensión mínima de ruptura del aislamiento, el nivel de PD, el cambio de campos eléctricos, etc., establece los valores de diseño adecuados para el diseño de cables de alta tensión. El estudio de campo eléctrico para este trabajo se ha realizado con el software ANSYS.

Palabras claves: Cable de alta tensión; Campo elctrico; XLPE; Aislamiento espeso; ANSYS.

Resumo

Este artigo discute os resultados de um estudo básico para o desenvolvimento de cabos XLPE de alta tensão (HV). Os autores estudaram os efeitos da alteração da construção básica de cabos de alta tensão para melhorar o design e o consumo de materiais dos cabos de alta tensão e estudar o efeito dessas mudanças na qualidade dos cabos de alta tensão fabricados. O estudo das propriedades do material XLPE, como a tensão mínima de ruptura do isolamento, o nível PD, os campos elétricos mudam e etc. para definir os valores de projeto adequados para o projeto de cabos de alta tensão. O estudo de campo elétrico para este trabalho foi feito com o software ANSYS.

Palavras-chave: Cabo de Alta Tensão; Campo elctrico; XLPE; Isolamento thickne; ANSYS

1. Introduction

The wire and cable industry, as one of the industries needed for the development of infrastructure in different countries, is an important industrial part. Today one of the main

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challenges facing this industry is the increase in the number of cable manufacturers, which has led to increased competition and, consequently, a reduction in the margin of profit. In such a situation, the need to increase productivity in different fields, along with the increased quality of the produced cable, is absolutely necessary. For this reason, during a four-year process, a research project aimed at increasing the quality of high voltage cables along with reducing material consumption and, consequently, reducing the cost of produced cables have done with the help of ABHAR CABLE Co., as one of the largest cable manufacturers in Iran. The following sections describe the steps involved in improving the design of this company's HV cables.

2. Background Of Research

The structure of HV cables with XLPE[78] insulation is as follows:

- Conductor: The main part of the cable used for electrical energy transmission.
- Internal semi conductive: creating a uniform cylindrical surface around external surface of the conductor to radialize the lines of the electric field inside the insulator
- XLPE Insulation
- External semi conductive: creating a uniform cylindrical surface for radialize distribution of electric field in the insulator.
- Semi conductive tape: Prevent deformation of semi conductive layer due to screen layer's pressure
- Screen: Creating a conductive metal surface to discharging and restricting the electric field
- Other layers are custom-made for mechanical protection.

The central core and indeed the most important part of a cable, is its conductor, in addition because of its energy transfer function, has a great influence on the design and material consumption in the cables, therefore, according to the researches and studies that carried out, the decision was made to optimize the diameter and external surface of the conductor and study its effect on the electrical properties of the cable.

3. Optimization Of The Diameter And External Surface Of The Conductor

A. Optimizations Parameters

HV cable's conductor is manufactured with different structures. Both copper and aluminum wire rods can be used in all these structures. In the conductor's manufacturing process, the final cross-sectional of conductor has been made by twisting the incoming wires. This part of cabling process is called stranding. In this process, in order to control the diameter of the output at each stage, dies should be used; these dies are commonly made of tungsten-carbide, PCD[79] or Nano Dies, each of which has its own characteristics. By passing stranded wires through these dies, because of the diameter of the stranded wire is greater than the diameter of the die, the stranded wires are compressed. By applying this pressure, the output diameter is controlled, gap between stranded wires are filled and the output surface will be smoother because of final die's pressure.

However, the compression percentage of the conductor varies according to the materials that used in construction of dies. In this company, tungsten-carbide dies was used and we changed that to Nano dies, and due to this change, we achieved to these advantages:

- ✓ Saving 2% to 3% copper and aluminum.
- ✓ Because of the smooth surface and extremely low. Friction characteristic of Nano-Dies, less energy is required to complete a compacting or stranding process.
- ✓ Less damage is done to the conductors in the process of being compacted.
- ✓ Lower electrical resistance because of minimizing the number of dislocations that occurs during compaction on the metal structure.

Decreasing the diameter of the conductor by increasing compression ratio.

B. Conductor optimization results

In the second stage of the conductor optimization process, the diameter of the input wires used in the last layer of the stranding

[78] Cross- linked polyethylene
[79] Polycrystalline diamond

process have decreased, which makes the conductor's outer surface smoother, and consequently, the sharp points at the external surface of the conductor reduced. Increasing the compression and changing the diameter of the wire used in the final layer of the stranding process reduces the final diameter and also smoothed the outer surface of the conductor. But to investigate the effect of these changes, three factors should be considered:

1) Conductor electrical resistance

Conductor electrical resistance is calculated with the following formula.

$$R = \frac{4\rho}{n.\pi.d^2} K_1 K_2 K_3 \quad \Omega/\mathrm{km}$$
(1)

ρ: resistivity at 20°C
For copper, ρ=17.241 $\Omega \mathrm{mm}^2/\mathrm{km}$
For aluminum, ρ=28.264 $\Omega \mathrm{mm}^2/\mathrm{km}$

n: number of wires in conductor
d: diameter of individual wires (mm)
K: factor to allow for the effects of manufacturing processes:
K1 for wire diameter and surface treatment
K2 for conductor stranding
K3 for core stranding

As can be seen in E. Peschke, R von Olshaun (1999), the electrical resistance has a direct relation with wire's length and reverse relation with the conductor's cross-section. Of course, in (E. Peschke, R von Olshaun (1999)), the cross-sectional area is referred to the actual cross-sectional area, which is the total cross-sectional of the wires used in the conductor construction. By compressing the conductor, the empty space between the interconnected wires is reduced and, as a result, the real cross-sectional has not changed, However, to prove this, the results of the electrical resistance testing of the conductors before and after the change can be seen in Table 1 (E. Peschke, R von Olshaun (1999)).

Table 1 Electrical test result about changing in used die's type and size in stranding process

cross section (mm2)	Final die dia. (mm)		Average conductor's measured electrical resistance (Ω/km)		Standard electrical resistance (IEC 60228) (Ω/km)
	tungsten -carbide	Nano Die	Old design	New design	
150	14.3	14	0.1238	0.1235	0.124
185	16	15.7	0.099	0.0988	0.0991
300	20.7	20	0.0600	0.0598	0.0601
400	23.2	22.8	0.0469	0.0468	0.0470
500	26.8	26.3	0.0365	0.0363	0.0366
630	29.3	29.8	0.0283	0.0281	0.0283

Nano-Dies have extremely low friction, hence less energy is required to complete a compacting or stranding process and less damage is done to the conductors in the process of being compacted. The damage which otherwise is done to the microstructure of the metal is in the form of dislocations in the crystal structure. The subject of dislocations is a major field of study within Physics and Metallurgy, but the bottom line is that every time a dislocation occurs, the electrical resistance of the metal increases slightly, due to the free electrons having slightly less freedom of movement than before. Nobody has yet developed a formula which can be used accurately to predict how much the electrical resistance increases for a given deformation, but some pictures of dislocations are available which clearly show the general idea. Hence, if the number of dislocations can be minimized by means of Nano-Dies and their very low friction surface, then the final electrical resistance of the cable will be lower. As shown in Table 1 with changing dies material and decreasing final diameter electrical resistance of the conductor is kept within the standard range.

2) In new desing, conductor's Surface is smoother than old conductor and consequently this improvement reducing the number of sharp tip points with high field density:

The case that was completely positive in changing the conductor's structure was that new design made the conductor's external surface smoother. The smoother surface helps semi conductive layer for eliminating the effect of the individual wires on the field distribution. This is due to the fact that the density of the electric field increases in the sharp points, and in cable this increase leads electric field in some places to exceed from the electrical breakdown field level of the insulation and thus increases the probability of the insulation failure. In the conventional design this issue is solved with the extruding semi conductive layer simultaneously with the insulation, by smoothing the outer surface of the conductor, consumption of this expensive semi conductive material, due to the reduction of semi conductive materials penetration into the conductor grooves, becomes less. Figure 1.

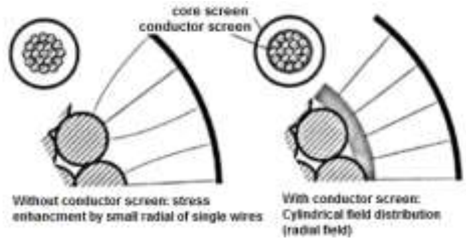


Figure 1 Principle of field equalization over a stranded conductor by using a conductive layer (E. Peschke, R von Olshaun., 1999)

In the process of improving design of the conductor, using semi conductive tape layer at the external surface of the conductor, before extruding semi conductive layer, in order to improve the conductor surface (eliminating sharp points) and also reducing the consumption of extruded semi conductive materials with the aim of preventing the penetration of the semi conductive materials into the conductor's surface grooves, is done (Umar Khayam et al., 2017). In this research the main effect of using this tape is changing relative permeability of inner semi conductive layer, this change's main reason is for controlling max. amplitude of electrical field in the insulation layer. Relative permeability's value for semi conductive material that used for conductor surface is about 11 and for insulation material (XLPE) is 2.3 according to electrical field equations when the electric field passes through two materials with different relative permeability, the electric field amplitude in these two regions is determined by relative permeability coefficient. In this article we purposed that with changing relative permeability of semi conductive layer in high voltage cables by adding a semiconductor tape layer, the effect of reducing the diameter of the conductor on the increase of the electric field is neutralized. This matter is explained in next section.

3) Electric field around the conductor

Due to the high operating voltage of HV cables, the range of electrical field created at the external surface of the conductor is very high. In the following, the electric field calculation method in HV cables is described.

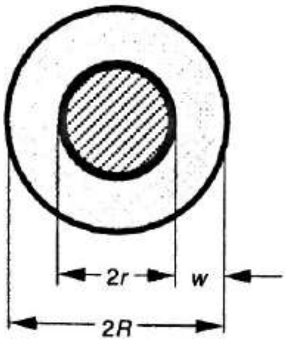


Figure 2 Cable cross section view[1]

Cylindrical electric field formula (Umar Khayam et al., 2017):

$$E(x) = U_0/\{x.\ln[(R)/r]\} \quad (2)$$

U0: phase voltage
r: conductor outer radial
R: radial of insulated cable
x: distance from cable central axis $r < x < R$

$$E_{max} = U_0/\{r.\ln[(R)/r]\} \quad (3)$$

$$E_{mean} = U_0/t \quad (4)$$

U0: phase voltage
t: thickness of insulation

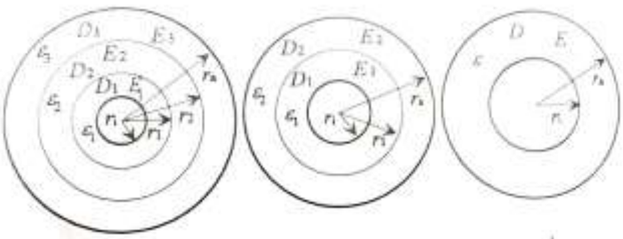


Figure 3 cylindrical capacitor with multi insulation layer

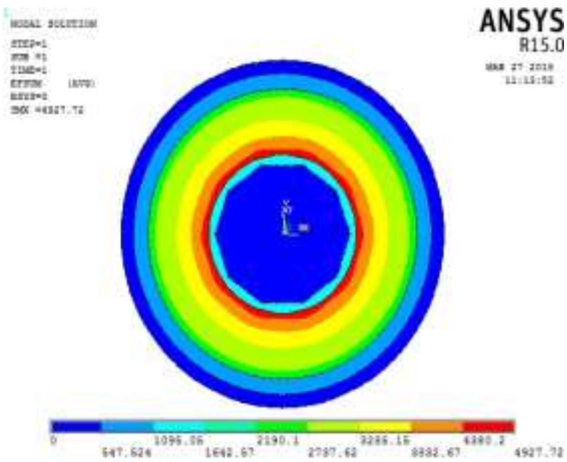
According to the (Illias et al., 2013 & Boukezzi et al., 2014) it seems that by decreasing overall diameter of conductor, maximum amplitude of electrical field will be increased and therefor according with (Qiliang 2000 & Boukezzi et al., 2014) with increasing the electrical field amplitude thickness of the insulation also should be increased, as it discussed in previous section the main solution for reducing the increase of the electric field is using semi conductive tape for controlling electric field. Each layer has own relative permeability and the amplitude of electrical field in each layer is related to other layers permeability and with changing this factor it seems that we can decrease maximum amplitude of electrical field in the insulation. This theory examined in three different cross section of 66 KV HV cable with the help of ANSYS software. Result of this simulation is shown in Table 2 and Figures 3 to 5.

Table 2 Insulation thickness and Max. electric field

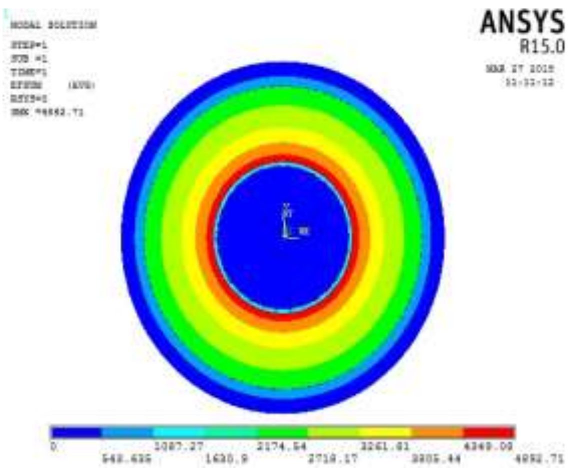
No.	Cable cross section (mm2)	Nominal Voltage (Kv)	Insulation thickness(mm)		Max. electric field (Kv/mm)	
			old	New	old	new
1	300	38/66	13	11	4.93	4.89
2	500	38/66	11.2	10.5	4.37	4.37
3	800	38/66	11.2	10.5	4.28	4.19

a. Electric field simulation

For considering new design's effects on cable, electrical field simulations have done with ANSYS. Results of these simulations illustrated in Table 2 and Figures 3 to 5.

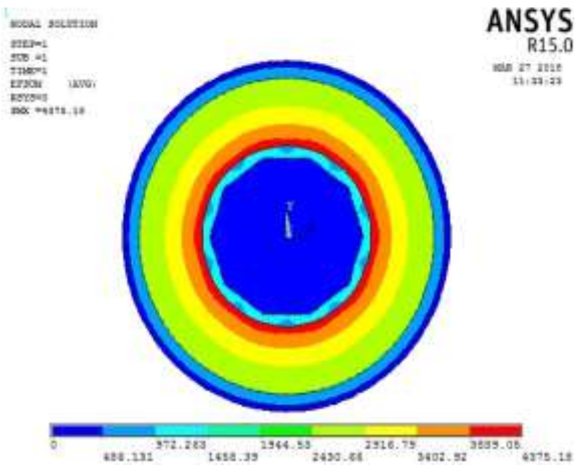


a) old design

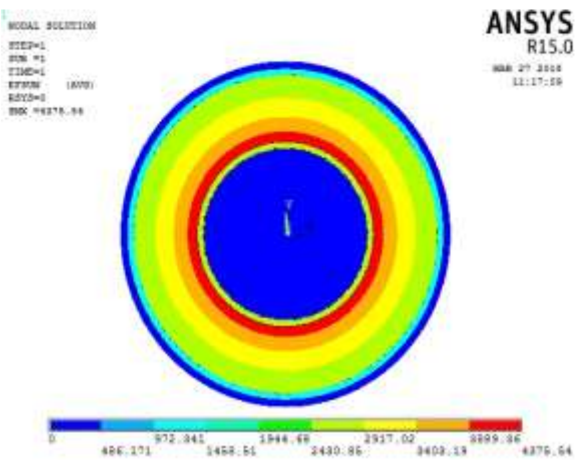


b) new design

Figure 3 Electric field in 300 mm2 (38/66 KV)

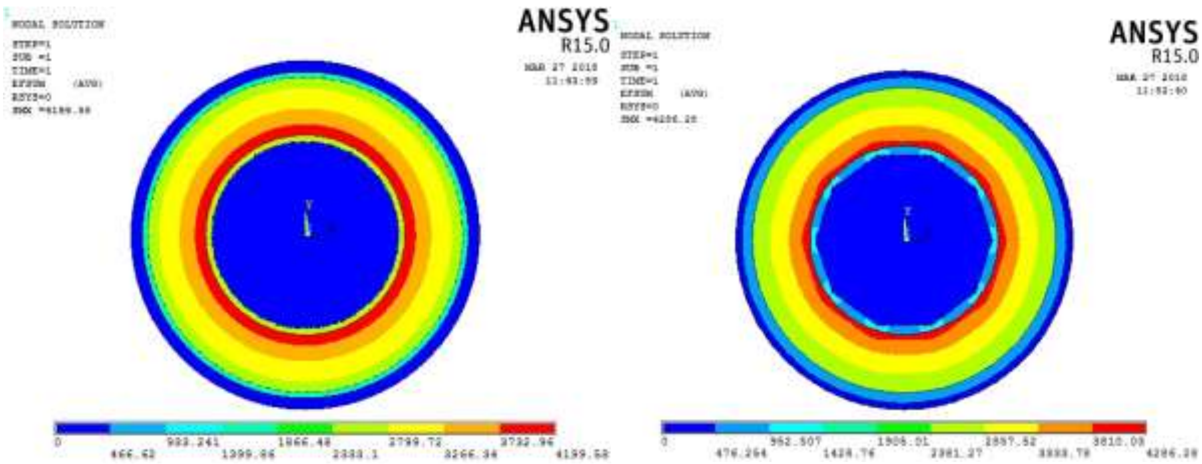


a) old design



b) new design

Figure 4. Electric field in 500 mm2 (38/66 KV)



a) old design b) new design

Figure V. Electric field in 800 mm2 (38/66 KV)

As it is shown in above figures changing of relative permeability of semi conductive layers reduce amplitude of max. electrical field. Simulation results show that amount of max. Field decreasing value is about 0.03 to 0.09 Kv/mm but for finding out of this changes effect with cooperating ABHAR CABLE company this three cables with mentioned dimensions has been produced and according with related standards of these cables, PD[80] tests have been done and results of this tests has been compared with similar cables that produced in company's routine. About 12 sample cable has been produced for each cross section and tested. PD results can be seen in nest section.

4. optimization of insulation thickness

Next step in HV cable design optimization is insulation thickness optimization. According to reference (Katakai 2002), the following factors and relationships are involved in calculating the thickness of the XLPE insulation.

AC design

$$t_{ac} = \frac{(U_0/\sqrt{3}) \times k_1 \times k_2 \times k_3}{E_{Lac}} \qquad (5)$$

Where

tac: insulation thickness needed for AC

U0: nominal maximum line voltage

K1: temperature coefficient

K2: degradation coefficient

K3: allowance for specimen test and other indeterminate elements

[80] Partial Discharges

ELac: minimum breakdown strength for AC

Impulse design

$$t_{imp} = \frac{BIL \times k_1' \times k_2' \times k_3'}{E_{Limp}} \quad (6)$$

Where

timp: insulation thickness needed for lightning impulse voltage

BIL: Basic impulse insulation level

K1': temperature coefficient

K2': degradation coefficient

K3': allowance for specimen test and other indeterminate elements

ELimp: minimum breakdown strength for imp

$$E_L(t) = A \times t^{-0.18} \quad (7)$$

t insulation thickness

A constant that obtained from weibull analysis and has different values for AC and Impulse

In insulation design for XLPE cable it is necessary to determine which is appropriate as the electric field notation: the average electric field (4) or maximum electric field on the internal semi conductive layer (3).
If both AC and impulse breakdown stress is expressed by Emean , it is roughly constant, not dependent to R/r, and if they are expressed by Emax , they tend to decrease as R/r gets greater. In E.Peschke, R von Olshaun (1999) a complete study has done about this and finally using of Emean for thickness calculation is chosen, also for studying the dependence of breakdown stress on size, an evaluation by weibull analysis is done. According to (Umar Khayam et al., 2017) results we decided to adopt Emean as the electric field notation.

As is shown in (Katakai 2002) EL value depends on the thickness of insulation. As the main cause for this, possibly, due to the fact that the manufacturing conditions are not always the same depending on the insulation thickness, differences arises in the insulation morphology in its thickness direction; for example, differences in the insulation thickness might cause changes in the crosslinking cooling conditions.

Therefore, by reviewing the previous designs and coefficients used in designing of the insulation thickness, which was performed with several experiments, optimal coefficients were determined according to the type of materials used. By using these coefficients, the thickness of the insulation was changed. These variations in insulation thickness for different cables are shown in Table 2.

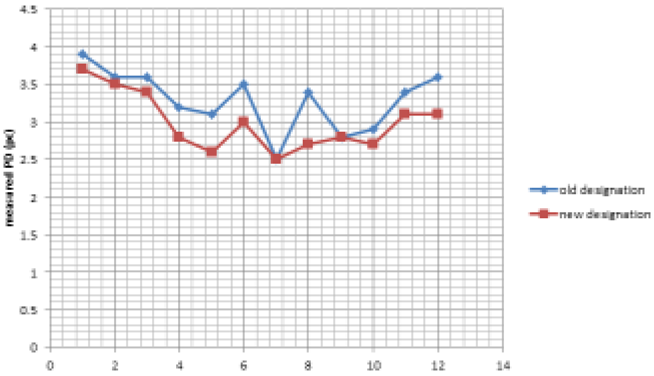


Figure 6 Measured PD in old and new design of 300 mm2 cable (38/66 kv)

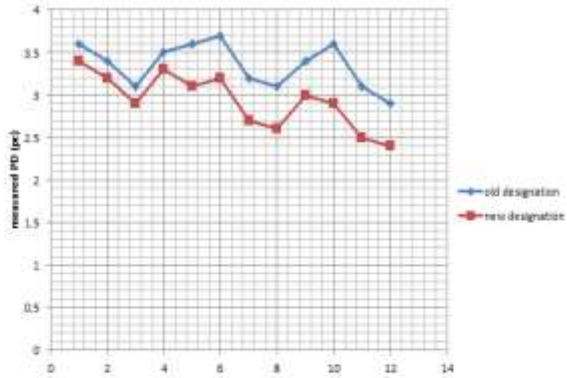


Figure 7 Measured PD in old and new design of 500 mm2 cable (38/66 kv)

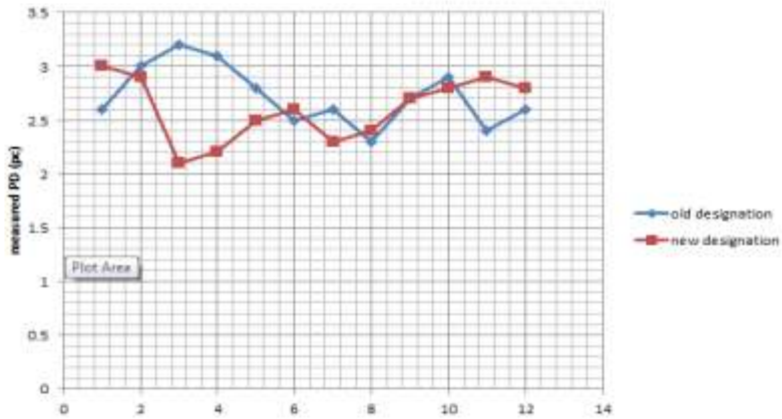


Figure VIII. Measured PD in old and new design of 800 mm2 cable (38/66 kv)

According to (E.Peschke, R von Olshaun (1999) & Grzybowski (1982)), with increasing insulating thickness, the probability of failure in cross-linking in the inner layers of insulation increases, and as a result, this increases the PD in the cable. By decreasing the thickness and diameter of conductors and controlling electrical field amplitude we need to study this changes effects on the cables quality so several PD tests have been carried out and results of these tests can be observed in Figures 6 to 8.

Results of PD tests show that in new design cables PD numbers are same or a little smaller than old design cables.

5. Effect Of Mentioned Improviment On Material Consupmtion Of Whole Cable

It was not necessary to modify other layers to improve the cable design, because by decreasing the final diameter of the conductor and thickness of the insulation, the design diameter of all layers will be decreased and as a result the materials of all stages of the cable manufacturing process would be reduced.

In Table 3 results of material consumption changes in new designed cables can be illustrated.

Table 3 Decreasation percentage of material usage in new designs

Layer name	300 mm2 cable	500 mm2 cable	800 mm2 cable
Inner semi conductive	-1.36%	-1.06%	-1.42%
Insulation	-20.66%	-8.57%	-10.21%
Outer semi conductive	-8.45%	-3.22%	-3.67%
Taping	-7.98%	-3.99%	-3.42%
Sheathing	-6.38%	-3.75%	-3.03%

According to Table 3, PD results and many necessary type and routine tests that should be performed on the HV cables and also simulation results during about four years study, we are be able to say our new designed cables are more efficient than old designed cables.

6. conclusion

As described above, we ascertained various basic constants for the improvement design of HV XLPE cables and verified various properties. In this part of study, evaluations were made concerning, design parameters such as electrical field stress, temperature coefficient, etc., As a results, highly reliable basic design constants were obtained. Using these constants conductor and insulation design for Abhar Cable Co. HV cables was accomplished, thus opening the way for realization effects of changes that happened in these cables quality.

With considering results of several years' studies and comparing results of various calculations and experiments, it has been observed that the mentioned optimization has been very effective and has a significant effect on increasing the productivity and competitiveness of HV cable manufacturers.

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