Design and mechanical properties of high-voltage transmission line composite insulators

Monika Fidanchevska, Bojan Mitev, Kristina Micova, Marko Naseski, Atanas Kochov
Ss. Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering, Skopje, Republic of North Macedonia

E-mail: fidancevskam97@gmail.com, bojanmitev77@gmail.com, kristina.micova@yahoo.com, marko.naseski2016@gmail.com, atanas.kochov@gmail.com

Abstract: *Design of high-voltage insulators with a capacity of 12 kV and 24 kV according to standard specifications and determination of the mechanical properties in virtual environment, as well as verification and validation of the results in laboratory conditions was the aim of this paper. The composition of the insulators was 50 vol. % epoxy resin and 50 vol. %* SiO_2*. Based on the physical and mechanical parameters of high-voltage insulators, 3D models were generated to correlate with them. Virtual simulations of the optimized models were performed by using SolidWorks software based on Finite Element Method. In order to re-examine the results, laboratory tests on physical specimens for determination of tensile, compression and three-point bending strength were conducted. The simulations were positively verified and gave promising results. The research conclusions show that the simulations in virtual environment provide easier and faster design and development of high-voltage insulators, which is of great importance for power transmission network industry.*

KEYWORDS: HIGH-VOLTAGE INSULATORS, VIRTUAL SIMULATIONS, COMPOSITE MATERIAL, POWER TRANSMISSION NETWORK

1. Introduction

There has been huge development in recent years in the field of electrical insulators manufactured from composite materials. Their application is highly dependent on their mechanical, electrical and thermal properties. Major transmission lines consider utilization of non-ceramic insulators and these have become more economically competitive with ceramic types. Composite insulators are beneficial because of their properties, such as: light weight, lower costs of transportation and construction, high strength to weight ratio, better contamination performance and also better transmission line aesthetics [1]. They are gradually replacing ceramic insulators for high voltage transmission and distribution. Various environmental factors (precipitation, pollution, winds, temperature variations) have huge impact on degradation of insulators. Flashover of insulators can cause interruptions in power supply. Therefore insulation performance is of great importance. Parts of composite insulator are: core material, end fitting and rubber insulating housing. The core distributes the tensile load, the end-fitting transmits the tension to the cable and the rubber housing provides electrical insulation [2]. Wide range of polymers are used for outdoor insulation applications, such as: silicon rubber, acryclic resin, nylon, epoxy resin, lignin etc. In order to reduce their drawbacks, suitable micro/ nano inorganic fillers like: zinc oxide, silica, titania, barium titanate have been added to the polymer matrix. Properties of composites can be modified due to the dispersion of the filler in the polymer matrix [3]. Epoxy resins have been of great importance for production of electrical insulators and in order to achieve better performance and commercialization they have been impregnated with inorganic microfillers such as silica. This inorganic microfiller provides not only excellent level of electrical insulation and mechanical strength, but also relatively low cost [4,5].

The utilization of CAD/CAM/CAE software plays important role in the rate and accuracy of decision making in tasks involved for insulators development for new applications. As maintained by the concept of concurrent engineering (CE), integrated system (CAD/CAM/CAE) could reduce the cycle of insulators design and production and proceed the manufacturing of insulators in a less time-consuming period [6].

2. Experimental

2.1 Technical specifications and 3D models of 12 kV and 24 kV high-voltage insulators

The dimensions of 12 and 24 kV insulators made in SolidWorks program are presented in (Fig.1) and suitable 3D models are presented in (Fig.2), respectively. The insulators were designed according to the prescribed standards for the size and dimensions. The design was created by following the basic form of insulators, with small changes in size, thickness and dimension of the ribs. However, height and diameter were maintained according to the standards. This design was obtained, because the insulator should be resistant to mechanical loads and natural influences (rain, atmospheric precipitations and other influences). Additionally, good aerodynamics, which is an important factor needs to be maintained.

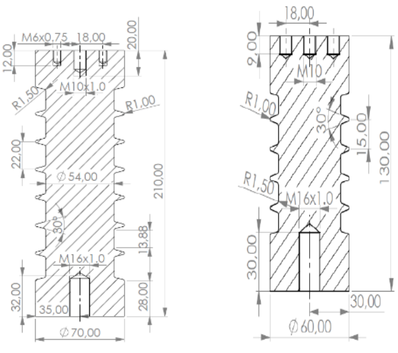

Fig. 1. *Design of 12 kV (left) and 24 kV (right) high-voltage insulator*

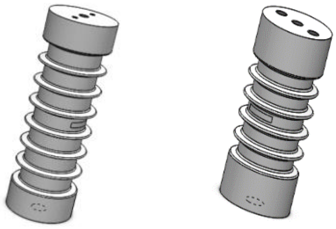

Fig. 2. *3D models of 12 kV (left) and 24 kV (right) high-voltage insulator*

2.2 Materials

Insulators were fabricated from composite material, consisting of 50 vol.% epoxy resin and 50 vol.% silica (SiO_2). As a matrix, two-pack epoxy resin system (epoxy resin and hardener) was obtained from TCM Triune Chemicals and Materials Co.(TCM HE2857/HH2857). Micronized silica with granulation less than 71µm was supplied by company Renova, Tetovo, Republic of North Macedonia.

2.3 Methods- static analysis and laboratory tests verification

The previously created 3D models, shown in (Fig.2), were analyzed via SolidWorks simulation, a static analysis. Simulations were performed according to the standard characteristics of each component and its ratio in the composite. The applied values for elastic modulus and tensile strength were 32820 N/mm^2 and 69 N/mm^2, respectively. In order to compare the 12 kV and 24 kV insulators, 100 kN force was used for each of the simulations. Additionally, the maximum force according to laboratory tests was used in simulation, in order to compare the values between simulations and laboratory tests. For obtaining more reliable results, the external forces and fixtures of the models in the simulations were made to match those of the real tests. Three operations were included in order simulation to be performed: applying external forces, determining the restriction of movement of the body and meshing the body, that are evident in (Fig. 3). Meshing is the process of subdividing the model into small pieces.

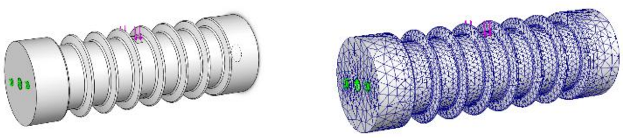

Fig. 3. *External forces and fixtures (left) and meshing (right) in simulation*

Finite element analysis looks at the model as networks of interconnected elements, therefore meshing is crucial in design analysis.
Mechanical testing of both types of insulators (12 and 24kV), shown in (Fig.4), was done in the accredited laboratory for testing of mechanical properties LT-04 at the Faculty of Mechanical Engineering in Skopje on a Shimadzu 25T AGX tensile testing machine.

Fig. 4. *Insulators 12 and 24kV (left), top surface (middle), bottom surface (right)*

3. Results and discussion

3.1 Compression test-static analysis

Compression simulations were performed by applying external, compressive force on the top surface. The 3D model of 12 kV insulator under compression force of 100 kN used during the simulation is evident in (Fig. 5). The bottom face was geometrically fixed. After simulation, maximum compression stress [N/mm^2], maximum displacement [mm] and maximum strain were attained and the results from the virtual compressive simulations are shown in Table 1.

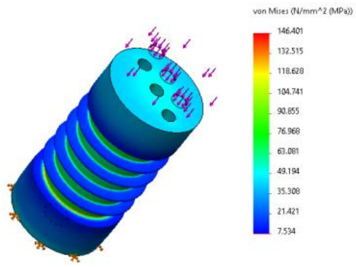

Fig. 5. *3D model of 12 kV insulator under compression simulation of 100 kN, maximum stress*

3.2 Compression test- laboratory test verification

Specimen was placed on flat surface and compressive force was acting on it. The force was transmitted through flat plate on the front surface of the insulator. In (Fig. 6) is evident specimen while being tested and the created breakage on its surface. Results for maximum stress, maximum displacement and maximum strain are apparent in Table 1.

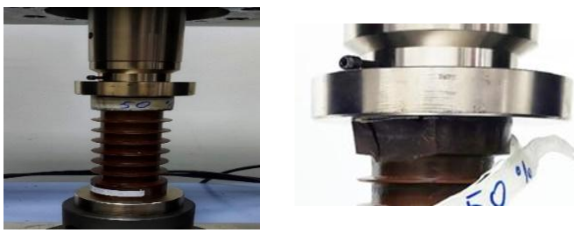

Fig. 6. *Compression test of insulator (left) and insulator after the test (right)*

Table 1: *Compression test- virtual static simulation and laboratory test*

Compression test	Simulation		Laboratory test
12 kV			
Force [kN]	100	207 075	207 075
Maximum stress [N/mm^2]	146.401	303.161	73.27
Maximum displacement [mm]	0.171	0.354	3.37
Maximum strain	0.003	0.006	
	24 kV		
Force [kN]	100	250 266.7	250 266.7
Maximum stress [N/mm^2]	112.046	280.402	65.06
Maximum displacement [mm]	0.218	0.546	4.48
Maximum strain	0.002	0.005	

3.3 Tensile test- static analysis

The external force was applied on the top face in the opposite direction comparing to compression test. 3D model after the simulation under force of 100 kN is evident in (Fig.7). The acquired results are presented in Table 2.

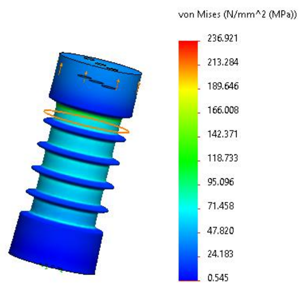

Fig. 7. *3D model of 12 kV insulator under tensile simulation of 100 kN, maximum stress*

3.4 Tensile test- laboratory test verification

In order the tensile test of insulators to be performed, screws were inserted into the specimens both ends. The tensile force was transmitted through the screws from the instrument. Given the composition of the material, as well as its brittleness, the destruction occurred in the joint of the built-in nut of the ends of the insulator, (Fig. 8). The results of tensile test are shown in Table 2.

Fig. 8. *Tensile test of insulator and insulator after tensile test*

Table 2: Tensile test- *virtual static simulation and laboratory test*

Tensile test	Simulation		Laboratory test
12 kV			
Force [kN]	100	18467.03	18467.03
Maximum stress [N/mm^2]	236.921	180.670	7.19
Maximum displacement [mm]	0.166	0.064	3.68
Maximum strain	0.005	0.004	
	24 kV		
Force [kN]	100	18219.23	18219.23
Maximum stress [N/mm^2]	272.099	106.404	5.08
Maximum displacement [mm]	0.222	0.063	4.35
Maximum strain	0.006	0.002	

3.5 Three-point bending test – static analysis

Three-point bending test simulation was conducted by applying external force on the middle of the insulator. The insulator was supported by the screws of the bending test machine and the force acting on the middle of the insulator. After the three-point bending simulation under force of 100 kN, 3D model is apparent in (Fig. 9) and the obtained results are shown in Table 3.

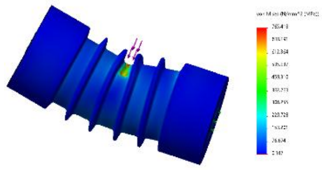

Fig. 9. *3D model of 12 kV insulator under three-point bending simulation of 100 kN, maximum stress*

3.6 Three-point bending test- laboratory test verification

The specimens were examined in the process of three-point bending, according to the standards prescribed for the test. The test was performed at a bending speed of 10mm/min. 12 kV insulator was ruptured close to the right support, at the three threaded inserts and built-in screws. On the other hand, 24 kV was broken in the middle of the length of the specimen, where force was acting, (Fig. 10). The obtained results are shown in Table 3.

Fig. 10. *Three-point bending test of insulator*

Table 3: *Three-point bending test- virtual static simulation and laboratory test*

Three-point bending	Simulation		Laboratory test
12 kV			
Force [kN]	100	24 760	24 760
Maximum stress [N/mm^2]	765.418	189.482	18.57
Maximum displacement [mm]	0.336	0.083	7.148
Maximum strain	0.016	0.004	
	24 kV		
Force [kN]	100	30 195	30 195
Maximum stress [N/mm^2]	546.861	172.547	24.42
Maximum displacement [mm]	0.588	0.178	7.148
Maximum strain	0.013	0.004	

4. Conclusion

Recent years have shown growing interest in the field of composite insulators for application in power transmission network. The crucial role is finding a suitable material that has improved properties comparing to conventional types. 3D modelling as well as virtual simulations are important for obtaining quite fast results with high accuracy.

This research saves time and money for manufacturers because potential errors would be identified in time and changes would be made before the product is ready to be presented on the market.

From this research it can be concluded that the insulators made from composite material consisting of 50 vol.% epoxy resin and 50 vol.% silica possess suitable properties for potential manufacturing. There is a difference between results in the simulations and laboratory conditions. In order to improve this, in real world conditions mixing of the materials need to be adjusted by inclusion of additives. In this way, air bubbles would be avoided and better dispersion of silica particles into the polymer matrix would be achieved.

High values of applied forces in laboratory conditions and possibility of insulators to withhold them provide information that they would be able to withhold them in manufacturing where more factors are included in the process.

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