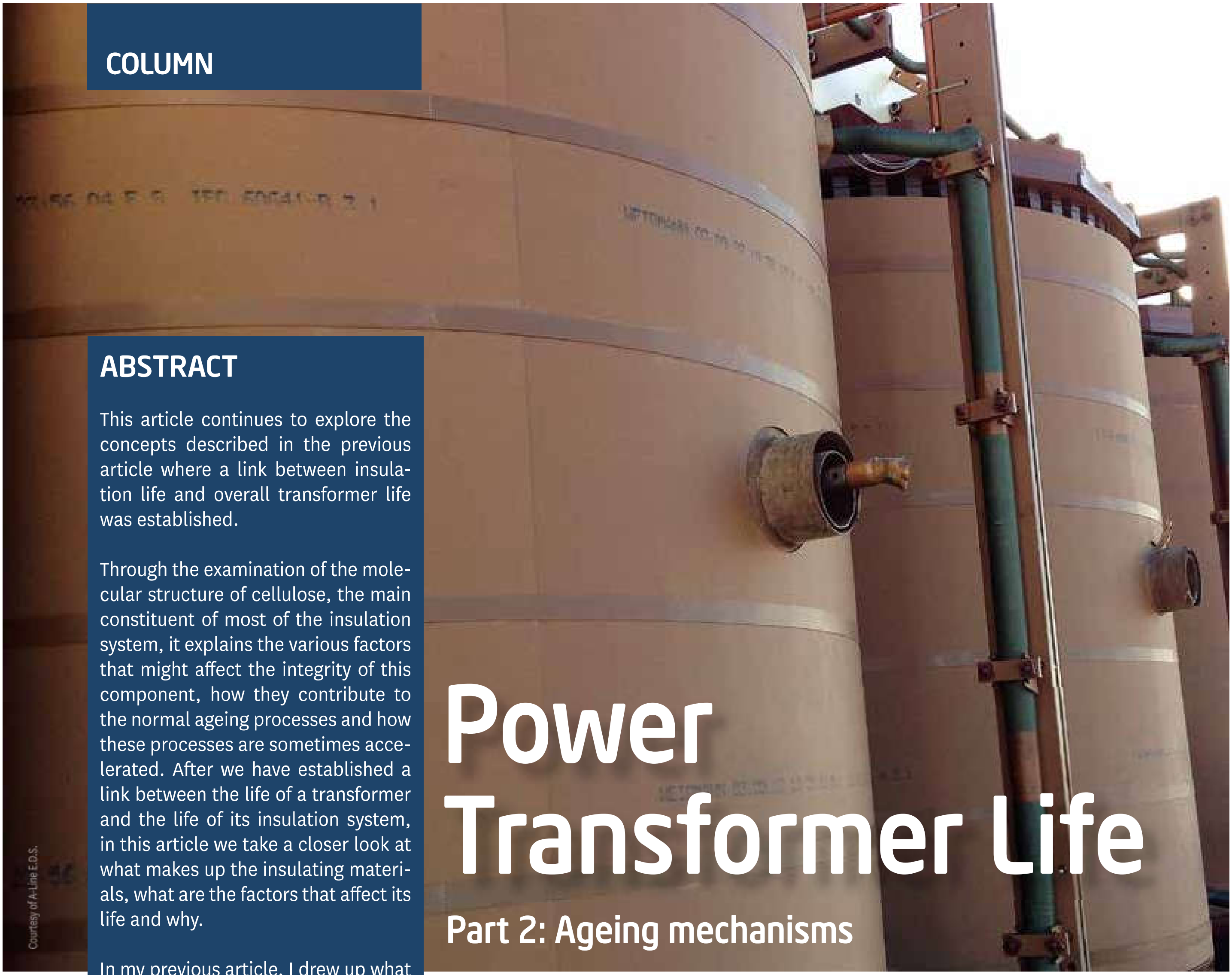

Courtesy of A-Line E.D.S.

Power Transformer Life

Part 2: Ageing mechanisms

ABSTRACT

This article continues to explore the concepts described in the previous article where a link between insulation life and overall transformer life was established.

Through the examination of the molecular structure of cellulose, the main constituent of most of the insulation system, it explains the various factors that might affect the integrity of this component, how they contribute to the normal ageing processes and how these processes are sometimes accelerated. After we have established a link between the life of a transformer and the life of its insulation system, in this article we take a closer look at what makes up the insulating materials, what are the factors that affect its life and why.

In my previous article, I drew up what I hope was a clear connection between what we call life in the context of a power transformer and the condition of its insulation system. We established that the life expectancy of a particular unit is intimately linked to the condition of the cellulosic material that makes up the bulk of its insulation system. The inquisitive reader would reasonably ask: “If the life of a transformer depends on the life of the insulation material, what then defines the condition of these materials?”

In this article, the second of our series of three, I will try to answer that question and provide you with a holistic picture of all the factors that have an effect on the life of insulation and why.

Keywords

power transformer, life, asset management, condition assessment, life extension, paper, insulation, cellulose

WHAT IS INSULATION MADE OF?

By now you have probably noticed that I have referred to the insulation material as “cellulosic”. At this point I must make a clear distinction. Although there is a wide variety of materials used in the design and manufacture of transformer insulation systems, the great majority of liquid filled transformers are built with cellulose based materials such as kraft paper, wood and compressed boards. Therefore, in this article I will focus our attention on this type of materials and not others, such as synthetic fibres, resins, epoxies, etc.

All insulation elements derived from vegetable fibres fall under the group I have been calling cellulosic materials. Whether the insulation takes the form of paper, tapes, compressed boards or blocks, their origin is the same, vegetable fibres.

The vegetable fibres that make up these materials are comprised by an organic compound known as cellulose. These molecules are also known as polysaccharides from the Greek root-words ‘poly’(many) and ‘sacchar’ (sugar). Surprised? Well, that is what vegetable fibres are made of, long chains of sugar molecules.

Another name that these types of molecules are known by is polymers, which means they are a collection of many monomers. In the case of the sugars forming the cellulose, the main constituents are carbon, hydrogen and oxygen, which is why they are also called carbohydrates.

This is better illustrated in the figure below, which shows the three-dimensional structure of this compound.

The vegetable fibres that make up these materials are comprised by an organic compound known as cellulose.

These cellulose polymeric molecules form long chains that in turn form the paper fibres. The photo below shows a microscopic view of these fibres under ultraviolet light.

Can you see how all the fibres interlace with each other? Well, that is what gives the paper its mechanical strength, which as we learned in the first article of this series, is a critical property for the life of the insulation system and the transformer as a whole.

The specific type of paper used in the construction of transformer insulation is also known as kraft paper (from the German word 'Kraft' for "strength") which is elastic, tear-resistant, non-bleached and consisting almost entirely of pure cellulose fibres.

Since the cellulose molecules are made up of a repetitive chain of basic sugar molecules or monomers, a common way of referring to the length of these molecules is by the average number of monomers that constitute them. In the transformer industry, this number is known as degree of polymerisation (DP).

In new transformer paper the average length of the cellulose molecules is around 1200 monomers or DP 1200. This DP number or the length of these molecules is directly coupled with the mechanical strength of the paper and the higher it is, the stronger the paper. As these molecules shorten due to the processes that we are going to discuss in the following section, the paper becomes more brittle and prone to mechanical failure. In extreme cases of very low DP the paper practically crumbles under any external force.

As a child, I used to observe how newspaper would become yellow and brittle after

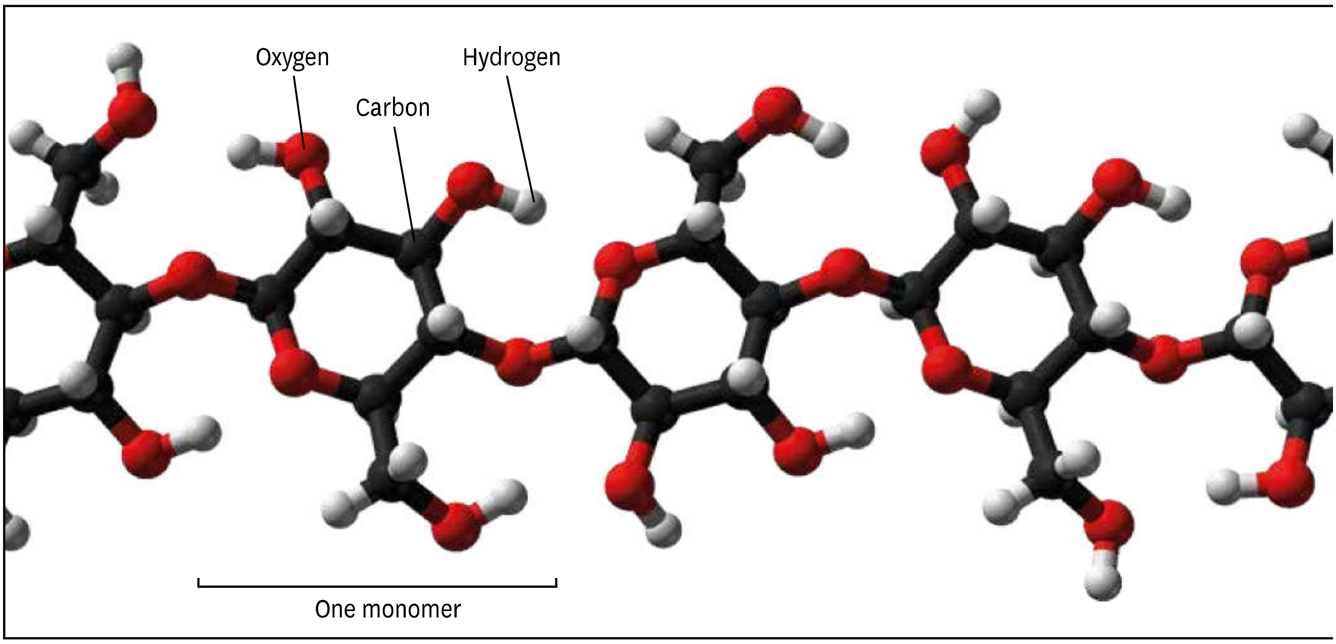

Figure 1: Cellulose molecule [1]

it had been left a few days under the sunlight. Now I understand why - the cellulose molecules were breaking down under the influence of the sun's heat. If you have ever seen this effect, that is exactly how an aged transformer insulation looks like.

Although the transformer will not immediately fail or explode when a low DP value is reached, there is a general consensus in the industry which is considered the end of transformer's life. This occurs when the paper has reached a point of mechanical strength so low that the transformer can no longer be considered to perform its function in a reliable manner. This number is normally considered to be a 200 DP.

So there it is. Your million-dollar investment will last the time it takes the DP to go from 1200 to 200.

The photo below depicts a section of a transformer coil that has reached this state. Although damage is not apparent at first sight, the paper in this particular coil would crumble as soon as touched.

Now that we know how the end of life is reached, let's examine what are the major causes that contribute to reaching this state.

So there it is. Your million-dollar investment will last the time it takes the DP to go from 1200 to 200.

THERMAL DEGRADATION OR PYROLYSIS

As we saw in the previous section, the paper ages as the cellulose chains break down and become shorter. Therefore, any mechanism that contributes to the breakage of the bonds between glucose monomers and the consequent shortening of these chains, can be considered an ageing or degradation mechanism.

First in our list is the degradation caused by thermal energy. Thermal energy can be contributed by either the normal production of losses during the energy conversion process which manifest in the form of heat or by anomalous localised energy sources caused by specific failure modes, such as increased resistance paths, short-circuits, etc. The heat energy released by these processes might increase the temperature of components in contact with insulation elements and result in degradation of this cellulose.

The increase in temperature increases the vibration of the molecules that constitute the cellulose and at some point, it breaks the bonds between the molecules, releasing by-products of this reaction into the oil and shortening the cellulose chains.

These by-products can include water (H2O), carbon monoxide (CO), carbon dioxide (CO2), organic acids and glucose molecules. These by-products can in turn exacerbate other degradation mechanisms.

HYDROLYTIC DEGRADATION OR HYDROLYSIS

It is not a coincidence that one of the primary focuses of installation and maintenance activities during the life of a transformer is the minimisation of water present in the insulation system.

In the presence of certain organic acids, a reaction is initiated with water that has the ultimate consequence of splitting the bonds between glucose monomers, which in turn produces more water and acid by-products.

As you might have suspected, this has a downward spiralling effect in which the reaction produces compounds that in turn favour additional reactions of the same nature which causes the whole cycle to repeat itself in an accelerated fashion.

Early experiments on the nature of this reactions showed that the life of the paper in terms of DP is halved every time the water concentration doubles.

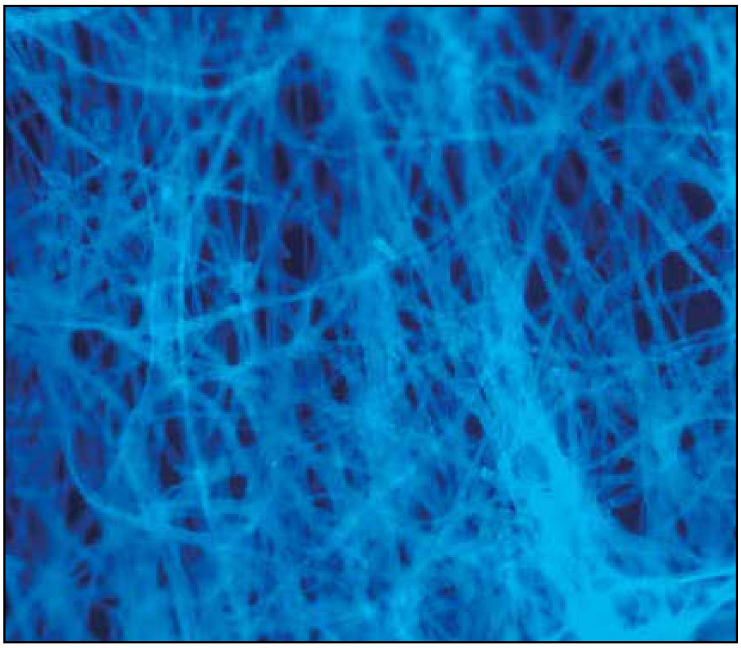

Figure 2: Cellulose fibres under ultra-violet light [2]

OXIDATION

In a similar way to hydrolysis, oxygen is a highly reactive element which causes the breakage of cellulose bonds to form by-products such as water, carbon monoxide and carbon dioxide.
These three mechanisms, oxidation, hydrolysis and pyrolysis normally do not act in isolation but rather as a group of reactions that reinforce each other.

ACIDS

Various organic acidic compounds are also released as by-products of the reactions described above. These acids in turn also attack the cellulose. In particular, the degradation of insulation due to acidic reactions has the consequence of producing sludge. As this sludge is produced, it could be deposited in areas critical for the cooling processes of the coils, such as cooling ducts, that would block the free circulation of oil, which in turn increases the temperature and accelerates the whole ageing cycle once again.

As we can see, there are a variety of mechanisms that cause degradation of the insulation system which effectively "ages" the transformer.

However, not all is bad news, the rate or speed at which these mechanisms take place can be monitored and actions can be taken to slow them down and extend the life of a transformer as much as practically possible.

In our next and last article I will talk about what practical measures are commonly taken to monitor and slow down these ageing processes in order to extend the life of transformers.

Figure 3: Example of a coil at its end of life [3]

Author

Carlos Gamez currently works as a Principal Consultant and Product Manager at TxMonitor and is a member of the MM Group Holdings where he focuses in developing innovative solutions for the electrical asset management industry using both his technical and business acumen.
After graduating in Electrical and Mechanical Engineering in 1996, Carlos started working as a Transformer Design Engineer at PROLEC-GE, the biggest transformer factory for General Electric on the American continent.
Over the course of the following years, he gained expertise working in various roles in product development, manufacturing improvements, technology and software development, field engineering and customer service.
In 2007 Carlos was seconded by General Electric to move to Perth, WA to start up the Transformer Division in order to provide field and workshop maintenance and repair services to customers across Australia.
Having fulfilled this mission, in the early 2011 Carlos accepted the position of Principal Consultant with Assetivity, a leading consultancy firm in Asset Management. Over this period, Carlos developed a holistic point of view by working on projects within the Asset Management frameworks which eventually shaped the ISO 55000 set of standards published in 2014.

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