Dry-type High Voltage Capacitors

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Abstract- **High voltage capacitors are important components of electrical network. The current technology is based foil-laminar coil impregnated in a liquid dielectric. However, there is an interest to develop technologies allowing to replace mineral or synthetic oil due both to health and environmental issues. The feasibility of replacing the impregnating liquid by a solid encapsulating material for HV capacitors is presented in this paper.**

I. INTRODUCTION

High-voltage (HV) film capacitors are important components for networks and various electrical devices. They are used either as coupling or capacitive voltage dividers, in electrical sub-stations, circuit breakers, for monitoring and protection devices, as well as to improve grid efficiency and reliability. For high voltage application, the most common technology is the wound foil-laminar configuration [1, 2] with coils connected in series and typically impregnated in oil in order to ensure the dielectric integrity and suppress any potential void that could lead to partial discharge (PD) activities in service as these devices operate at relatively high geometrical electrical stresses (~35 kV/mm). However, although current HV capacitors impregnated with synthetic oil have a high electrical reliability, the use of oil, particularly synthetic oil, raises some concern as they could potentially be forbidden for either environmental or safety issues. It is indeed possible that new environment protection and preservation regulations entering in force could prohibit their use in a few years. Accordingly, there is an interest to find alternative encapsulating materials. One of the possible candidates is low-viscosity impregnating epoxy resin appropriate for Vacuum Pressure Impregnation (VPI) process, and prior reports have shown the potential of this technology [3, 4].

In order to evaluate the feasibility of dry-type capacitors with a rated voltage of 1.5 kV per coil (corresponding to about 40 kV/mm) an investigation was carried out on both the optimization of the processing parameters and the electrical performance of such capacitors. The replacement of oil in the capacitor by a suitable thermosetting resin system without reducing the electrical performances is a challenging task and requires a lot of re-engineering and re-design. The influence of every materials and parameters used was evaluated during the course of this project and led to both selection of appropriate materials and the optimization of the fabrication process for capacitors ranging from one to twenty wound coils (corresponding respectively to approximately 70 to 3.5 nF) assembled in series. To achieve a proof-of-concept, the geometry of the reference wound coil was fixed by industrial considerations related to real fabrication facilities.

Moreover, the research and development phase needed deep comprehension of the effect of every step of the fabrication process from single materials performances and limitations to their assembly interactions leading sometimes to presence micro-cavities and PD during the electrical tests. Phase Resolved Partial Discharge (PRPD) was used as the main quality control tool and with the use of this non-destructive technique, it was possible to implement a qualification procedure in order to assess the performance of multi-coil dry-type capacitors. This paper will present the electrical performance of the dry-type capacitors along with a qualification procedure based mainly on PRPD measurements leading to recommendations for further improvements. The physicochemical kinematics of the curing of the thermosetting resin will appear in a different report where a general correlation between all processing parameters and the PRPD measurements will be presented.

II. MATERIALS AND FABRICATION PROCEDURE

Due to a combination of technical and practical reasons, the final wound coil arrangement that was selected consisted of 5 µm-thick aluminum foils separated by a set of three dielectric layers made of ruggedized biaxially oriented polypropylene (PPR) each having a thickness of 12.7 µm. These layers were corona treated in order to increase their compatibility with the impregnating resin, which did not lead to any significant increase of the material dissipation factor that remained low (~10^{-4}) [3]. This later material will be referred as PPRC. More details on this configuration was presented elsewhere [1, 3]. Probably the most critical parts of the coils' assemblies are the coil-to-coil connections and the final two end-connection topologies. In the case of a capacitor made of a single coil there was obviously not coil-to-coil connection but just two end-connection wires. Unlike what it is used in the industrial standard procedure, here the two external connectors were manually added to the multi-coil capacitors, which was found to yield better performance. Once the multi-coil or single-coil capacitor was assembled with the end-connectors, the assembly was then introduced into a suitable mold for thermosetting resin impregnation and curing process. For this purpose, a Vacuum Pressure Impregnation (VPI) technique [3, 5] has been developed and the various processing parameters were optimized. The manufacturing process can be summarized in two main phases: the first one is carried out under vacuum and the second one under pressure. Initially, in order to remove moisture as much as possible

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inside the coils' assembly with a combination of heat and vacuum, molds containing pre-conditioned unimpregnated wound coils are introduced inside an oven. Then, the thermosetting resin is prepared and degassed under vacuum. Once the resin is properly degassed, it is transferred into the molds and then the impregnation of the coils' assembly occurs. The second main phase takes place under pressure with suitable curing parameters into an autoclave. This step allowed to reduce the size of any bubble that might be present into the liquid thermosetting resin and between layers, reducing or eliminating the presence of cavities and defects. Finally, after the completion of the curing process, a solid encapsulated capacitor is obtained. More details on the fabrication procedures are provided elsewhere [3] and will also lead to a future report.

III. TESTING PROCEDURE

In order to assess and optimize the fabrication process, 38 dry-type capacitor samples with multiple numbers of coils up to 20 (~3.5 nF, 30 kV rated voltage) were fabricated using the procedure previously described.

The electrical tests consisting of capacitance, dissipation factor and PRPD measurements, the later test being the most critical, were conducted on all samples. Capacitance and dissipation factor measurements were carried out using a dielectric spectrometer (Broadband Dielectric Spectrometer (BDS) from Novocontrol Technologies) for which capacitance and dissipation factor (or tanδ) were measured within a frequency range from 0.1 Hz to 1 MHz at room temperature. PRPD measurements were carried out with a MPD600 system from Omicron, a Phase-Resolved Partial Discharge (PRPD) monitoring system.

IV. EXPERIMENTAL RESULTS

A. Dry-type capacitor fabrication

Previous works [1, 3] carried out on dissections of single wound-coil samples confirmed that a three-layered dielectric wall was an appropriate geometrical arrangement for dry-type capacitors. In addition to the impact of the processing parameter on the capacitors' performance, the impact of the type of end-connectors (commercial vs lab-made) and the type of consolidating frames were also investigated. Furthermore, several materials and compaction parameters led to different trials in order to find the suitable combination allowing to reduce or prevent the formation or creation of intra-layers cavities.

B. Electrical tests – capacitance and dissipation factor

In order to evaluate the functionality of each sample, the encapsulated capacitors were removed from the autoclave and electrically characterized as soon as the sample reached room temperature. Capacitance and loss factor at 60 Hz of single wound coil with three different technologies for dielectric wall were compared in a previous work [3]: three-layer PPRC, three- and one-layer non-corona treated PPR. For multi-coil capacitors made of 5, 7, 9, 14 or 20 coils in series with the three-layer PPRC configuration, it was observed that the capacitance at 60 Hz was in good agreement with the expected results (according to the geometry and the permittivity of PP). Fig. 1 shows the average capacitance obtained for each type of multi-coil capacitors. Fig. 2 presents the corresponding dissipation factor values, which were reasonably low ($< 4.5 \times 10^{-4}$) and would comply with the usual requirements for this type of capacitors. In Fig. 1 and Fig. 2, each value corresponds to the average on number of capacitors of the same size (same number of coils) manufactured with the same fabrication process. The influence of temperature was also investigated. As it can be seen in Fig. 3 and Fig. 4, when the capacitance and dissipation factor of 5 different dry-type capacitors were measured as a function of temperature in the -15 to 80 ºC range, the dissipation factor was found to remain relatively low below 80 ºC and the capacitance was found to vary from +1,0% to -2.0% (compared with the value at 20 ºC).

C. Electrical tests – PD measurements

PD measurements were carried out in after the capacitance and dissipation factor characterization. The PD test bench consists on a PRPD measuring system including a PD-free capacitive coupler connected in parallel with the sample under test. As mentioned before this is the main quality control test as the quality of the fabricated capacitors is largely related with absence or the scarcity of cavities, defects or impurities inside the layered structure of the tested sample. In a previous report, PD results for single-coil capacitors were reported with the tests carried out at nominal voltage (1.5 kV), corresponding to an internal electrical field of 40 kV/mm [3]. Fig. 5 shows the linear relationship between number of coils assembled in series and the related voltage that needed to be applied in order to maintain a nominal electric field of 40 kV/mm, which obviously is a linear relation since the voltage divides equally across each coil in series. The PD histograms shown in Fig. 6 and Fig. 7 are in the usual format (several manufacturers of PD equipment use the same), which is the x-axis representing the phase of the applied voltage, the y-axis the PD magnitude (in C) and the color code represents a digitalization of the number of PD of that magnitude at that phase position per second. The green curve is the applied voltage.

Before carrying out the PD measurements it was necessary to do a preliminary background noise (BG) measurement for baseline conditions without any applied voltage. An example of such baseline behavior is presented in Fig. 6. This was followed by the actual PD measurement at 40kV/mm. Fig. 7 presents a 1-minute test for a 5-wound coil sample. In that case, even if there is an increase of the Q_{IEC} value as compare to the BG, since this increase is not correlated with the applied voltage it can be concluded that the test capacitor doesn't show any sign of partial discharges. Such general phase-independent increase the PD level was commonly observed in most of the tested samples and accordingly the single Q_{IEC} value does not give the whole story.

To properly compare PD measurements, it was found to be preferable to record the relative IEC's apparent electric charge (Q_{IEC}), this relative Q_{IEC} being obtained by subtracting the absolute Q_{IEC} value and the one obtained from the BG noise. Fig. 8 presents the average of relative Q_{IEC} for dry-type capacitors with 5, 7, 9 and 14 wound coils. Even if the samples tested at 40 kV/mm did not present a phase-related PD pattern, the trend shows that Q_{IEC} increases with the number of coils. Because of the voltage limitation of our PD testing experimental setup, 14-coil capacitors could only be tested at 37.5 kV/mm. For similar reasons, 20-coil capacitors were fabricated and tested at 26.3 kV/mm (which is below nominal voltage). Results showed an absence of PD at this level for most of the samples, but due to the fact that these capacitors were not tested at the nominal field of 40 kV/mm, this data point was not considered in Fig. 8. The results of the electrical characterization of the multi-coil capacitors are summarized in Table I. It is relevant to mention that among the 38 samples fabricated with the same fabrication procedure, only four showed phase-related PD patterns. These four samples were removed for the average calculation of relative Q_{IEC} since they were not representative do to unsuccessful fabrication. Nevertheless, the 4 out of 38 number can be viewed as the rejection rate of the current fabrication process and it is believed that with further improvement of the process including more automated and less manual operations, this rate could be significantly decrease.

TABLE I

MULTI-COILED CAPACITORS COMPARISON RESULTS

Number of coils	5	7	9	14	20
E_{test} (kV/mm)	40	40	40	37.5	22.3
Number of samples	13	10	4	2	9
PD presence with a PRPD pattern	None	1/10	1/4	None	2/9
Average relative Q_{IEC} (pC)	0.4	1.92	1.58	2.29	3.27

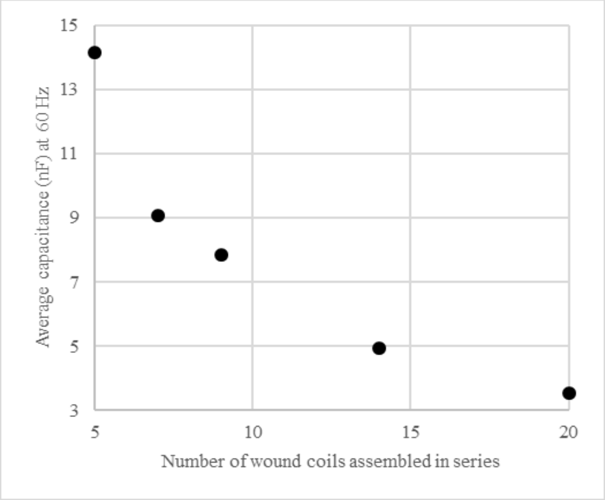

Fig. 1. Average capacitance at 60 Hz as a function of the number of coils in series.

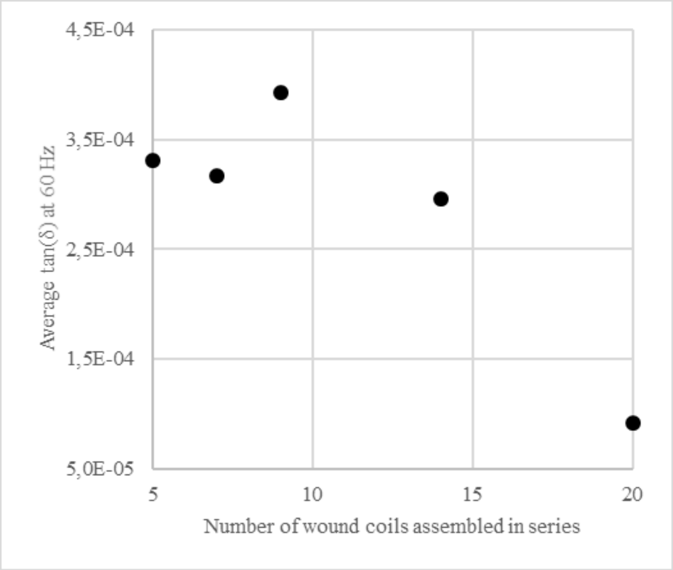

Fig. 2. Dissipation factor at 60 Hz as a function of the number of coils in series.

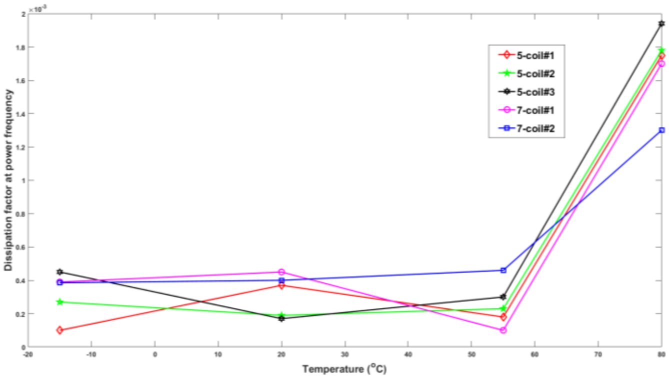

Fig. 3. Varition of dissipation factor for 5- and 7-coil dry-type capactors as a function of temperature.

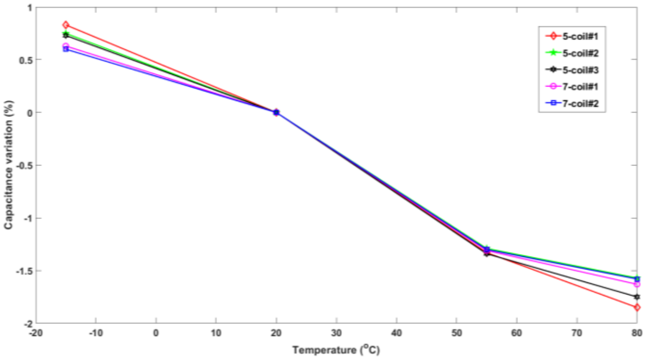

Fig. 4. Varition of capacitance for 5- and 7-coil dry-type capactors as a function of temperature.

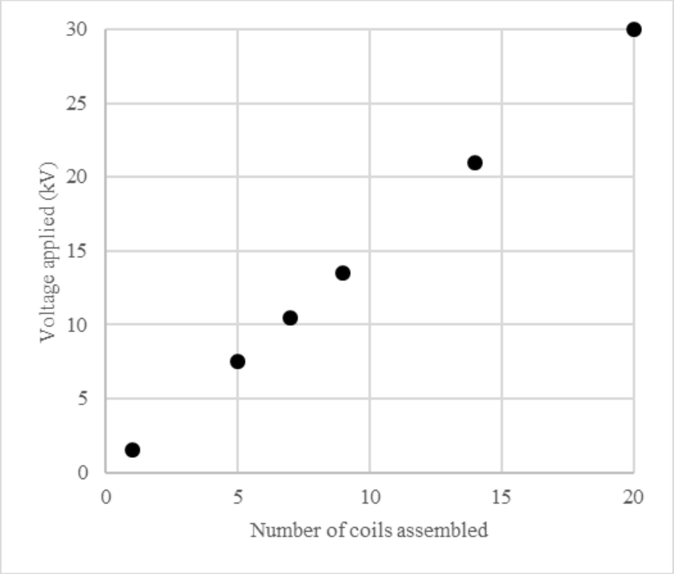

Fig. 5. Variation of the applied voltage as a function of the number of wound coils for a dry-type capacitor rated 1.5 kV per coil (~40 kV/mm).

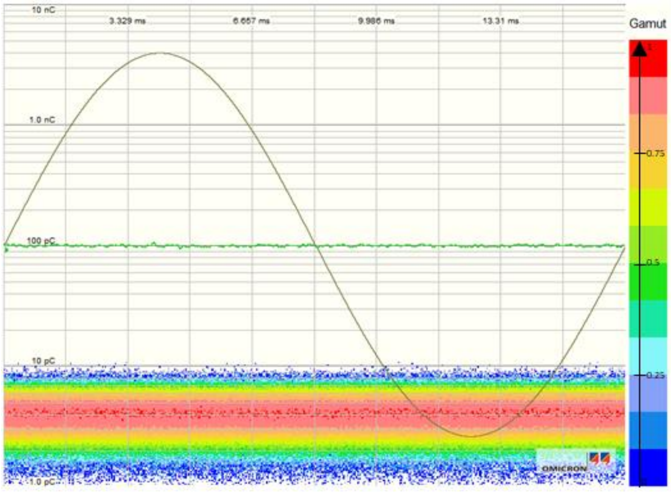

Fig. 6. PD histogram of the background noise for a five-coil dry-type capacitor.

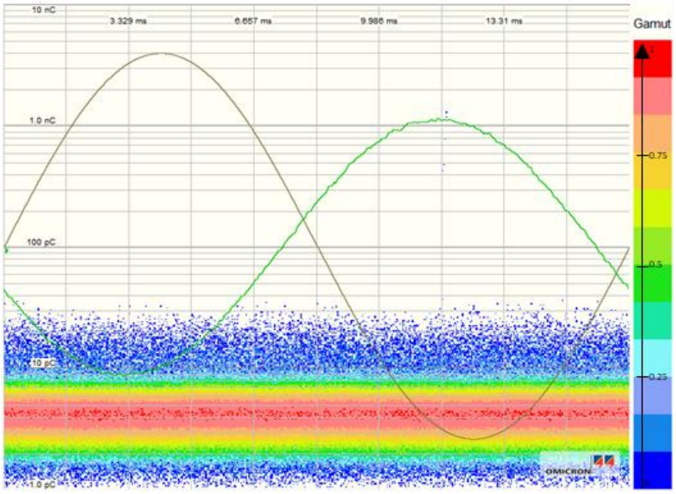

Fig. 7. PD histogram for a five-coil dry-type capacitor at 40 kV/mm.

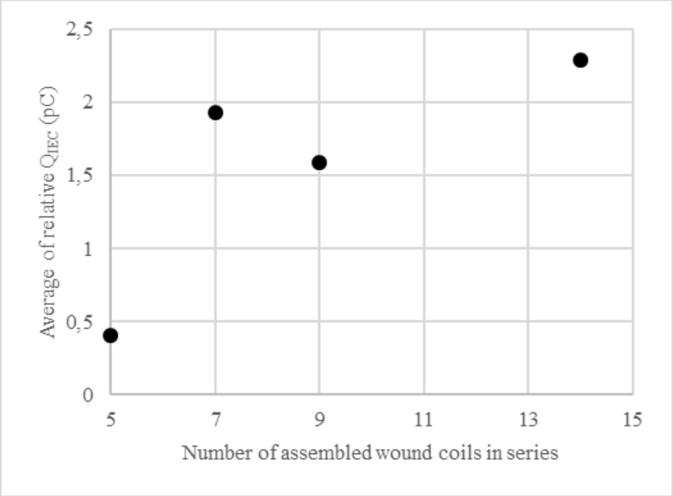

Fig. 8. Average of standardized Q_{IEC} (PD-BG) related to the number of wound coils connected in series for a dry-type capacitor rated 1.5 kV per coil (E~40 kV/mm).

V. CONCLUSIONS

The preliminary results presented in this report are believed to be a proof-of-concept of the use of VPI process in order to replace synthetic oil by a thermosetting resin for HV capacitors. The developed fabrication process led to confirmation of the feasibility of manufacturing dry-type high voltage capacitor by using all-film wound coils encapsulated in a thermosetting resin. However, an investigation of the behavior of such capacitor under outdoor conditions remains to be assessed. Furthermore, the inclusion of encapsulated active parts in a suitable HV capacitor housing still remains to be designed in order to produce an industrial prototype that could lead to serial production.

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