CHRONICLING THE DEGRADATION OF A 345 kV GENERAL ELECTRIC TYPE U BUSHING

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ABSTRACT

Prior to ITC Holdings Corp assuming ownership of the transmission system in the state of Michigan there had been a series of catastrophic failures involving 300 MVA transmission system transformers. As a part of ITC's investment in the grid, a transformer monitoring project was initiated to allow real-time monitoring to mitigate imminent transformer failures. Although the project had been initiated in 2002, another failure of a 675 MVA, 230 kV phase shifting transformer in 2004 provided further justification for a transformer monitoring project.

ITC Holdings Corp underwent the exercise of evaluating commercially available transformer monitoring systems. The scope was to implement on-line monitoring on all transformers rated 120 kV and above. Aspects of the transformer that would be monitored included temperatures, dissolved gases and bushings. This paper will review the data captured by the bushing on-line monitoring system that lead ITC Holdings Corp to take a 370 MVA, 345 kV autotransformer out of service and correlate it with off-line measurements that resulted in permanently removing the bushing from service. The findings from the subsequent factory testing and dismantling of the bushing led by Hubbell Power System's PCORE Electric will illustrate how changes in power factor are manifested in a bushing insulation system.

BACKGROUND

The wye configured 345/129 kV, GE autotransformer was manufactured in 1986. The 370 MVA transformer is an asset of ITC's 345 kV transmission system and is a critical link for an independent power producer. The on-line monitoring system for this transformer was implemented during the spring of 2007. At the time of commissioning all the high voltage winding and neutral bushings were GE Type U, the low voltage winding bushings consisted of two Lapp POC and one ABB Type O+C. As part of the commissioning process, off-line capacitance and power factor measurements were performed on all of the bushings. The results are listed in Table 1 and Table 2.

TABLE 1
April 2007 Bushing Off-line C1 Test Results

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Cap(pF)	IR_{auto}
H1	1796658	.26	401	10.005	1.487	0.0440	0.30	394.40	G
H2	1797914	.27	407	10.006	1.509	0.0680	0.45	400.26	D
H3	1797916	.26	406	10.004	1.501	0.0450	0.30	398.03	G
X1	96-71129	.26	377	10.008	1.421	0.0450	0.32	376.83	G
X2	3030410394	.24	385	10.007	1.420	0.0420	0.29	376.67	G
X3	96-71113	.26	381	10.005	1.429	0.0430	0.30	379.14	G
N	2176999	.29	535	10.009	2.052	0.1350	0.67	544.41	I

TABLE 2
April 2007 Off-Line C2 Test Results

ID	Serial	NP %PF	NP Cap (pF)	Test kV	mA	Watts	%PF corr	Cap (pF)	IR_{auto}
H1	1796658	.305	4973	3.000	18.705	0.4140	0.22	4961.5	G
H2	1797914	.237	5338	3.000	20.171	1.287	0.64	5350.4	D
H3	1797916	.235	5317	3.000	20.063	0.4420	0.22	5321.8	G
X1	96-71129	.28	1952	3.001	7.342	0.2470	0.34	1947.4	G
X2	3030410394		4329	3.000	16.217	0.4310	0.27	4301.7	G
X3	96-71113	.29	1959	3.000	7.374	0.2500	0.34	1956.0	G
N	2176999			0.5000	2.720	0.1390	0.51	721.42	D

The tests revealed elevated power factor results for the H2 and the neutral (N) bushings. It was also discovered that the neutral bushing was leaking oil from the test tap which the crew was able to temporarily repair. Another outage was scheduled for early 2008 to perform extensive maintenance on the transformer. With the need to return this asset to service the decision was made to rely on the bushings' monitoring system until the next scheduled outage. It needs to be noted that a neutral bushing cannot be monitored while it is in service because of the lack of voltage potential across its dielectric.

February 2008 the GE transformer was removed from service for scheduled maintenance, at this time the H2 and neutral bushings were replaced. The bushing nameplate information with the new H2 and neutral bushings installed is listed in Table 3.

TABLE 3
Bushing Nameplate Information as of March 2008

Dsg	Serial	Mfr	Type	C1 %PF	C1 Cap	C2 %PF	C2 Cap	kV	Amps	Year
H1	1796658	GE	U	.26	401	.305	4973	220	800	1986
H2	05-105312	Lapp	POC	.27	492	.25	6081	345	800	2007
H3	1797916	GE	U	.26	406	.235	5317	220	800	1986
X1	96-71129	Lapp	POC	.26	377	0.28	1952	102	2000	1996
X2	3030410394	A-BB	O+C	.24	385		4329	102	2000	1994
X3	96-71113	Lapp	POC	.26	381	.29	1959	102	2000	1996
N	04-218906	Lapp	PRC	.68	464			25	1200	2007

Prior to returning the asset to service all the bushings were retested; the results are shown in Table 4 and 5. These results will serve as a reference for the subsequent discussion of the on-line bushing measurements.

TABLE 4
March 2008 Off-Line C1 Test Results

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Cap(pF)	IR_{auto}
H1	1796658	.26	401	10.007	1.488	0.0410	0.28	394.74	G
H2	05-105312	.27	492	10.007	1.869	0.0500	0.27	495.89	G
H3	1797916	.26	406	10.007	1.502	0.0430	0.29	398.36	G
X1	96-71129	.26	377	10.011	1.421	0.0380	0.27	377.03	G
X2	3030410394	.24	385	10.008	1.420	0.0390	0.26	376.74	G
X3	96-71113	.26	381	10.007	1.431	0.0390	0.27	379.57	G
N	04-218906	.68	464	10.008	1.739	0.1090	0.60	461.26	G

TABLE 5
March 2008 Off-Line C2 Test Results

ID	Serial	NP %PF	NP Cap (pF)	Test kV	mA	Watts	%PF corr	Cap (pF)	IR_{auto}
H1	1796658	.305	4973	3.001	18.786	0.4070	0.22	4983.1	G
H2	05-105312	.25	6081	3.001	22.769	0.5290	0.23	6039.7	G
H3	1797916	.235	5317	3.001	20.054	0.4320	0.22	5319.4	G
X1	96-71129	.28	1952	3.001	7.344	0.2650	0.36	1948.1	G
X2	3030410394		4329	3.001	16.212	0.4270	0.26	4300.3	G
X3	96-71113	.29	1959	3.001	7.370	0.2690	0.36	1955.0	G
N	04-218906			.5000	10.898	0.7920	0.73	2890.6	G

CHRONICLE THE DEGRADATION OF THE H1 BUSHING

The transformer was returned to service during the middle of March 2008. The on-line monitoring system utilized on these bushings tracked the capacitance and power factor, the diagnostic system was configured to issue alarms if various thresholds for capacitance and/or power factor were exceeded. At 5AM on July 10, 2008 the bushing diagnostic analysis issued its first alert, indicating the power factor of the H1 bushing had exceed the first of a series of thresholds. The condition persisted at each subsequent hourly recording. On the morning of July 11th the data was off loaded and sent to Doble for further review.

The on-line bushing diagnostic system utilizes three time intervals to track changes in capacitance and power factor; one day (24 data points) one week (168 data points) and one month (672 data points). Short intervals are utilized to identify sudden changes in the bushing; however these are more susceptible to external influences. The longer trending periods tend to be more representative of the bushing's condition and less affected by system fluctuations, however the longer intervals require more data to react to changes. Stability of the data needs to be taken into consideration when triggering a notification of an anomaly for any threshold settings; thus shorter trending intervals typically need to be set higher.

In this instance, the alert being generated by the expert system was based on the monthly trend of the H1 bushing's power factor that had exceeded the 1% threshold. A review of the last three months of data revealed that the H1 bushing had been manifesting an increase in power factor, and that increase had accelerated during the second week of June. As of the morning of July 11th the on-line expert system was reporting a power factor for the H1 bushing of 1.3% based on monthly trending, the capacitance had remained stable over this period and there were no significant changes in the other bushings.

The nature of the power factor change was characteristic of a degrading bushing and the lack of abrupt changes in the measurements led Doble to conclude that the on-line results were representative of the current condition of the bushing. ITC was advised to schedule an outage in the near future to corroborate the on-line results with off-line tests. On July 21st at approximately 6AM the unit was taken out of service. The last on-line measurement, which was at 5AM, indicated a power factor of 1.59% for the H1 bushing and the capacitance was 400 pF (based on month trending). The results for the off-line bushing C1 and C2 power factor and capacitance tests and C1 tip-up tests are listed in Table 6, 7 and 8.

TABLE 6
July 2008 Off-Line C1 Test Results

ID	Serial	NP % pF	NP Cap (pF)	Test kV	mA	Watts	%PF corr	Cap(pF)	IR_{auto}
H1	1796658	.26	401	10.020	1.502	0.2190	1.36	398.47	I
H2	05-105312	.27	492	10.018	1.888	0.0470	0.25	500.74	G
H3	1797916	.26	406	10.015	1.511	0.0360	0.22	400.78	G
X1	96-71129	.26	377	10.010	1.436	0.0390	0.27	380.91	G
X2	3030410394	.24	385	10.009	1.428	0.0340	0.26	378.87	G
X3	96-71113	.26	381	10.008	1.445	0.0400	0.28	383.29	G
N	04-218906	.68	464	10.010	1.778	0.0990	0.64	471.67	G

TABLE 7
July 2008 Off-Line C2 Test Results

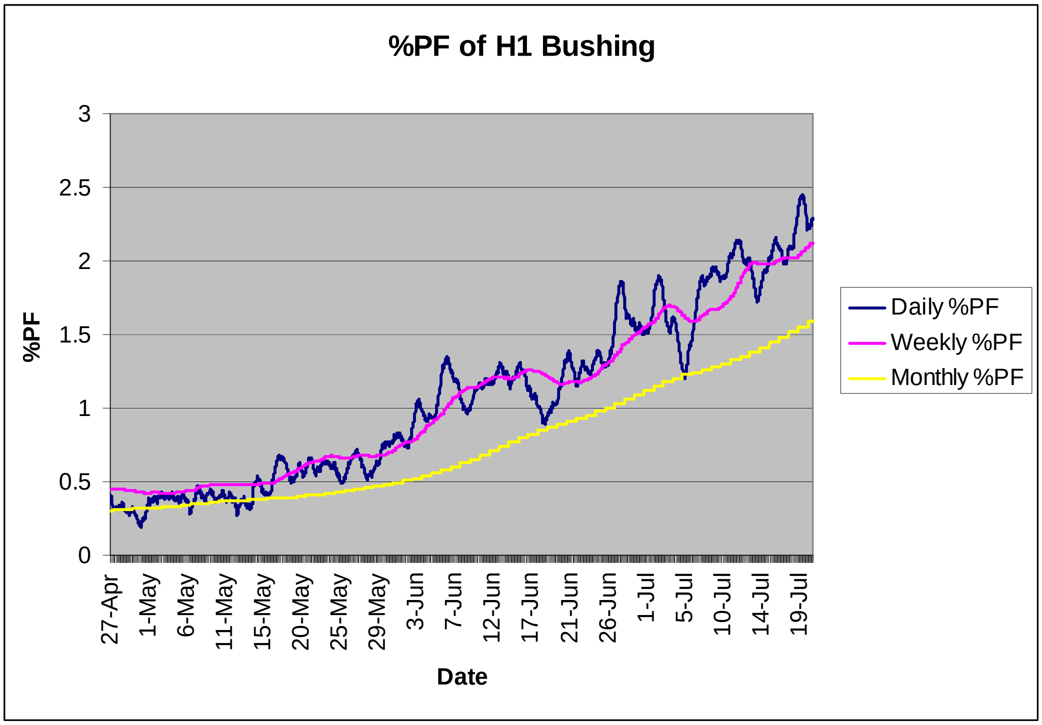
ID	Serial	NP %PF	NP Cap (pF)	Test kV	mA	Watts	%PF corr	Cap (pF)	IR_{auto}
H1	1796658	.305	4973	3.001	18.768	0.725	0.39	4978.2	G
H2	05-105312	.25	6081	3.001	22.877	0.5060	0.22	6068.2	G
H3	1797916	.235	5317	3.001	20.147	0.4290	0.21	5344.1	G
X1	96-71129	.28	1952	3.001	7.383	0.2490	0.34	1958.4	G
X2	3030410394		4329	3.001	16.282	0.3960	0.24	4318.8	G
X3	96-71113	.29	1959	3.001	7.414	0.2750	0.37	1966.5	G
N	04-218906			.4990	11.148	0.703	0.63	2957.0	G

TABLE 8
July 2008 Off-Line C1 Tip-Up Test Results

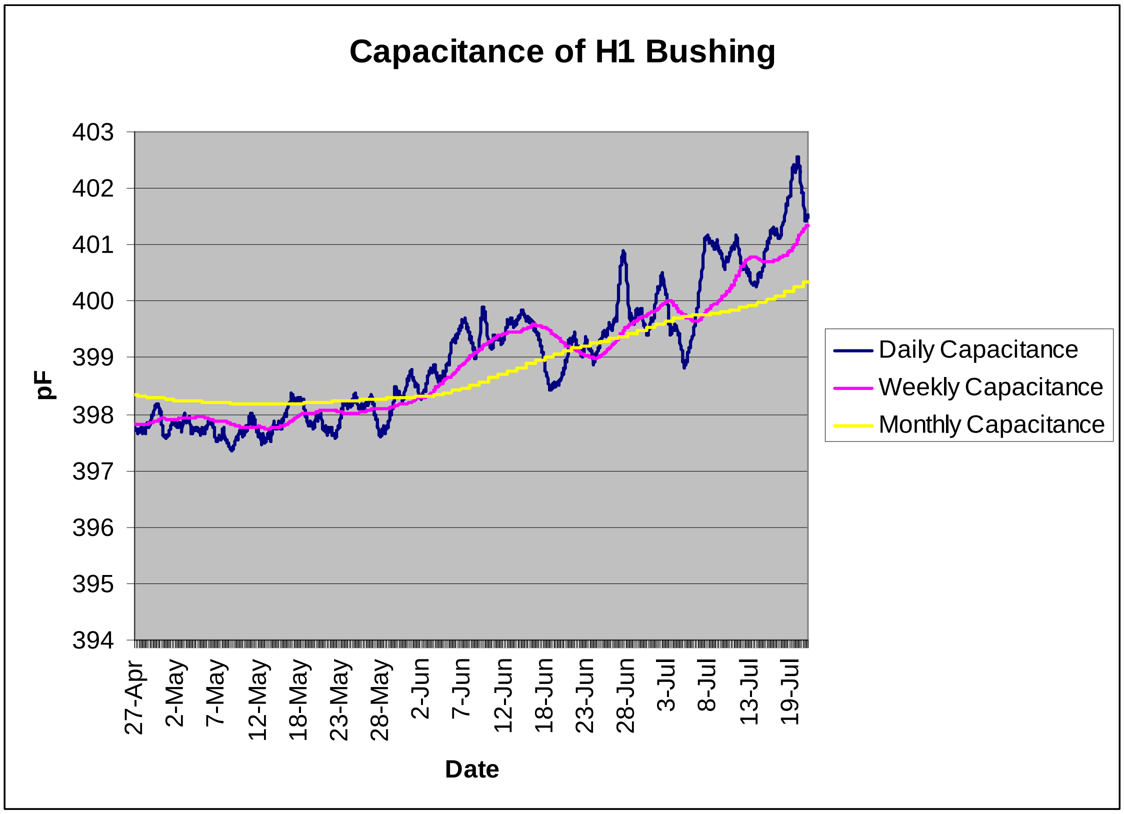
ID	Serial	Test kV	mA	Watts	%PF corr	Cap (pF)
H1	1796658	2.000	1.502	.1960	1.30	398.50
H1	1796658	4.003	1.503	.1980	1.32	398.52
H1	1796658	6.005	1.502	.2020	1.34	398.51
H1	1796658	8.010	1.502	.2070	1.38	398.44
H1	1796658	10.012	1.502	.2130	1.42	398.37

DISCUSSION OF ON-LINE DATA

Figure 1 plots the H1 bushing's power factor from April 27th through July 21st , this was calculated from the on-line leakage current measurement at the bushing tap using the three trending intervals; Figure 2 represents the capacitance calculation utilizing the same information. With reference to the monthly data, shown in Figures 1 and 2, a correlation between the on-line data reported by the monitoring system can be made with the off-line test results shown in Table 4 and 5 (performed in March). Both of which suggest that little or no degradation of the H1 bushing had occurred up to that point. The power factor results exhibit a very gradual increase through the end of May when the power factor is approximately 0.5%, after this the rate increases more significantly. The overall increase in capacitance is far less significant and on its own does not justify an investigation. Both the on-line and off-line results indicate that the deficiency is related to the quality of the dielectric and not to the physical composition of the bushing.

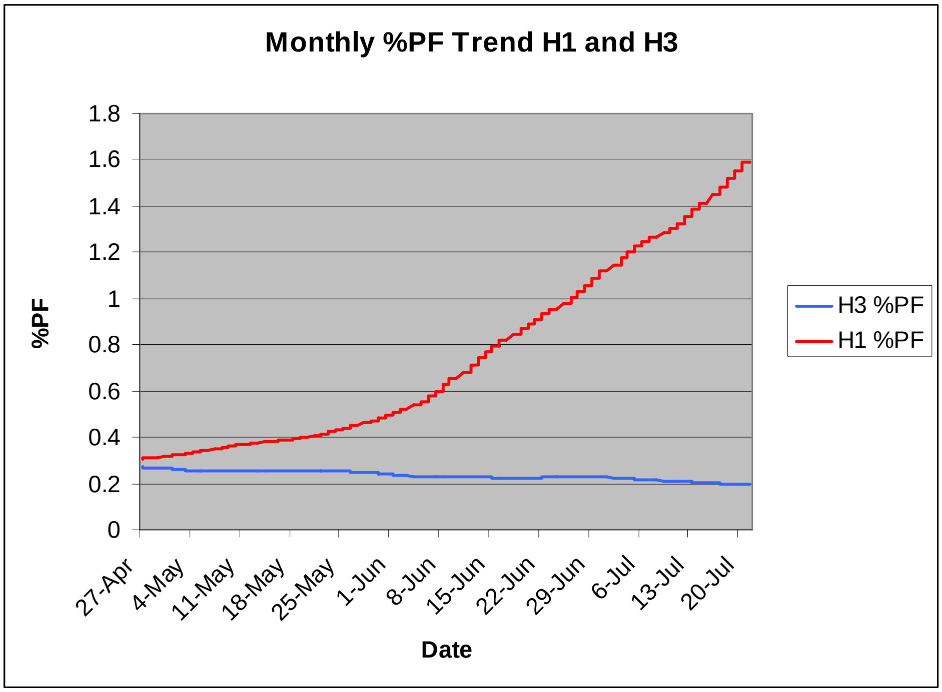


% Power Factor of H1 Using On-line Measurements
FIGURE 1

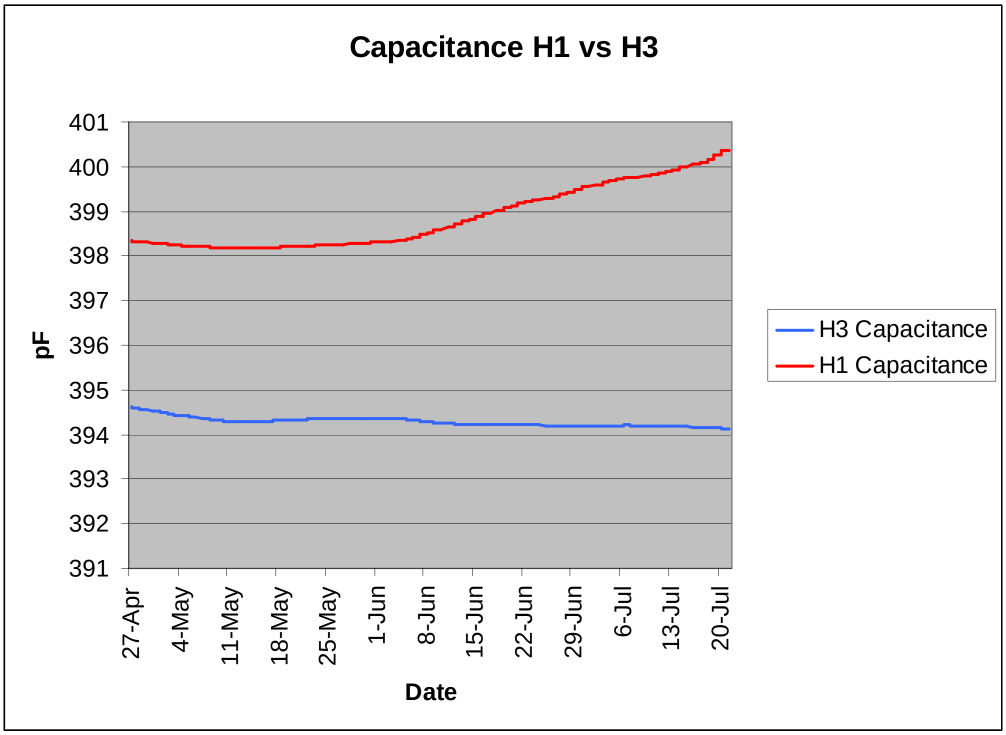


Capacitance of H1 Using On-line Measurements
FIGURE 2

Figure 3 represents the monthly power factor trend of the two non referenced bushing, H1 and H3, which correlates well with their off-line measurements. Figure 4 goes through a similar exercise using the capacitance of the H1 and H3 bushings.



% Power Factor of H1 and H3 Bushing Using On-line Measurements
FIGURE 3



Capacitance of H1 and H3 Bushing Using On-line Measurements
FIGURE 4

RESULTS OF DIELECTRIC FUILD ANALYSIS

Table 9 contains the dissolved gas analysis of the oil sample drawn from the H1 bushing after it had been removed from service. The results (in ppm) exhibit elevated levels of hydrogen and a small amount of acetylene which is a characteristic of partial discharge.

TABLE 9
DGA Results

Gas	Chemical Formula	Measured Levels (PPM)	IEC 61464 Limits (PPM)
Hydrogen	H_2	6020	140
Oxygen	O_2	12600	
Nitrogen	N_2	52000	
Methane	CH_4	1280	40
Carbon Monoxide	CO	229	1000
Ethane	C_2H_6	570	70
Carbon Dioxide	CO_2	783	3400
Ethylene	C_2H_4	3.1	30
Acetylene	C_2H_2	0.9	2

The oil quality tests indicate the dielectric fluid was acceptable for service and the Furanic concentration suggest very little paper aging had taken place. These results are shown in Table 10 and 11.

TABLE 10
Oil Quality Results

Top Oil Temp	^{o}C	15
Water Content	ppm	6
Relative Saturation	%	13
Dielectric Strength D1816	kV	36
Interfacial Tension	dynes/cm	41
Neutralization Number	mgKOH/g	<0.01
Power Factor 25 ^{o}C	%	0.078
Power Factor 100 ^{o}C	%	2.430
Specific Gravity	60/60	0.877

TABLE 11
Furanic Compounds

Hydroxymethyl-2-furfural (HMF)	Ug/L	<1
Furfuryl alcohol (FOL)	Ug/L	<1
2-furaldehyde (FAL),	Ug/L	<1
2-acetylfuran (AF)	Ug/L	<1
5-methyl-2-furfural (MF)	Ug/L	<1
Overall FAL Rate	Ug/L/Year	0.05

BUSHING DISSECTION

Even though the H3 was not manifesting any anomalies, give the recent events associated with H1 and H2 bushings, ITC Holdings Corp opted to remove it from service. The H1 and H3 bushings were shipped to the PCORE Electric plant in LeRoy NY, where they were to undergo remanufacturing. In the interest of this paper PCORE Electric offered to perform supplemental tests and to dismantle the bushings with the intent of assessing the extent of the degradation.

Prior to dismantling the bushings a series of electrical tests were conducted at the manufacturer's facility; which included C1 and C2 capacitance, power/dissipation factor measurements and partial discharge evaluations. The power factor and partial discharge results are listed in Table 12. It is noted, the C1 power factor test results had retracted from the results obtained in the field which could suggest a temperature related problem. However, the factory results confirm that the condition of the bushing was deteriorated. The 10 kV C1 power factor test result was close to twice the nameplate while the 200kV (line to ground rating) was approaching three times the nameplate. The partial discharge test revealed 200 pC of apparent energy at operating voltage with an inception voltage of 143kV. Clearly partial discharge was occurring in the bushing. The assembled H1 bushing was also pressure tested to 20PSI, but this did not reveal any leaks. However, the bushing was found to be leaking internally into the center conductor.

TABLE 12
Factory C1 Power Factor and Capacitance and
Partial Discharge Tests

Schering Bridge					
H1, Serial Number 1796658			**H3, Serial Number 1797916**		
kV	**%DF**	**Capacitance**	**kV**	**%DF**	**Capacitance**
10	0.486	404 pF	10	0.234	409 pF
50	0.574	404 pF	50	0.235	409 pF
100	0.615	404 pF	100	0.239	409 pF
150	0.615	404 pF	150	0.240	409 pF
200	0.602	404 pF	200	0.242	409 pF

Partial Discharge		**Partial Discharge**	
10	2-3 pC	10	2-3 pC
50	2-3 pC	50	2-3 pC
100	2-3 pC	100	2-3 pC
143	60-70 pC	143	2-3 pC
150	70-90 pC	200	2-3 pC
200	150-200 pC	220	2-3 pC
Ambient = 2-3 pC		330	2-3 pC
		Ambient = 2-3 pC	

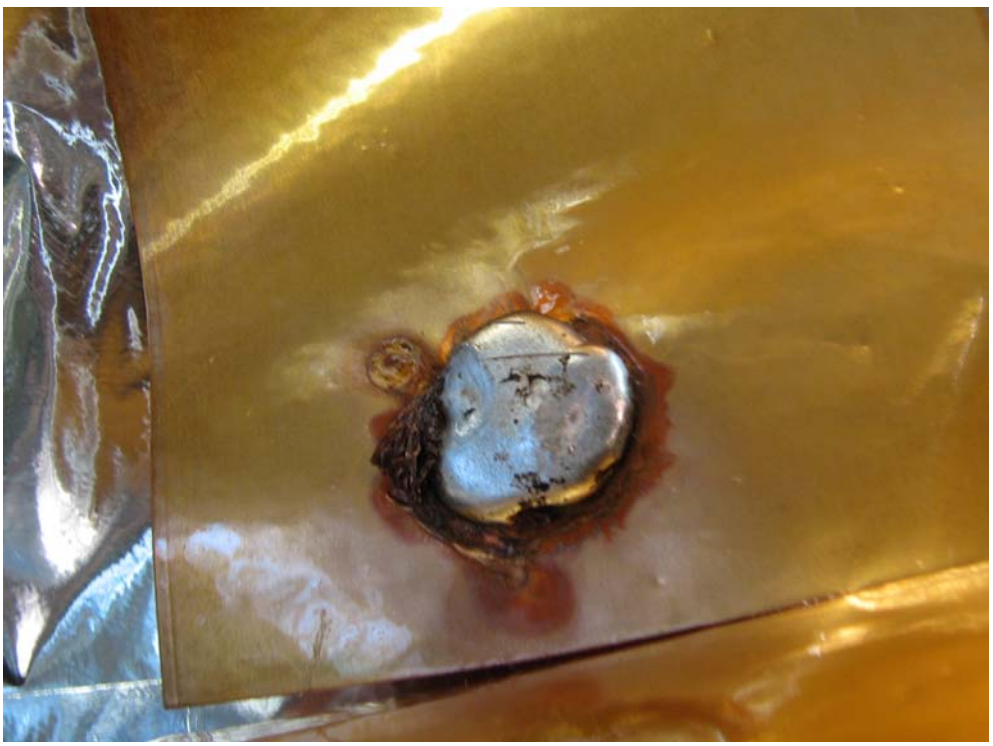
Figure 5 shows the bushing in tack, and Figure 6 illustrates the bushing with the outer weather shed removed. The bushing condenser design employed electrical grade paper with a metallic foil layer periodically incorporated in the wrapping. The core construction consisted of 440 turns of paper and 42 foil layers. This design eliminated one of the more common failure mechanisms of the GE Type U bushing which is ink migration (herringbone design) to the insulating layer, which may lead to partial discharge and/or overheating of paper.

H1 Bushing Intact
FIGURE 5

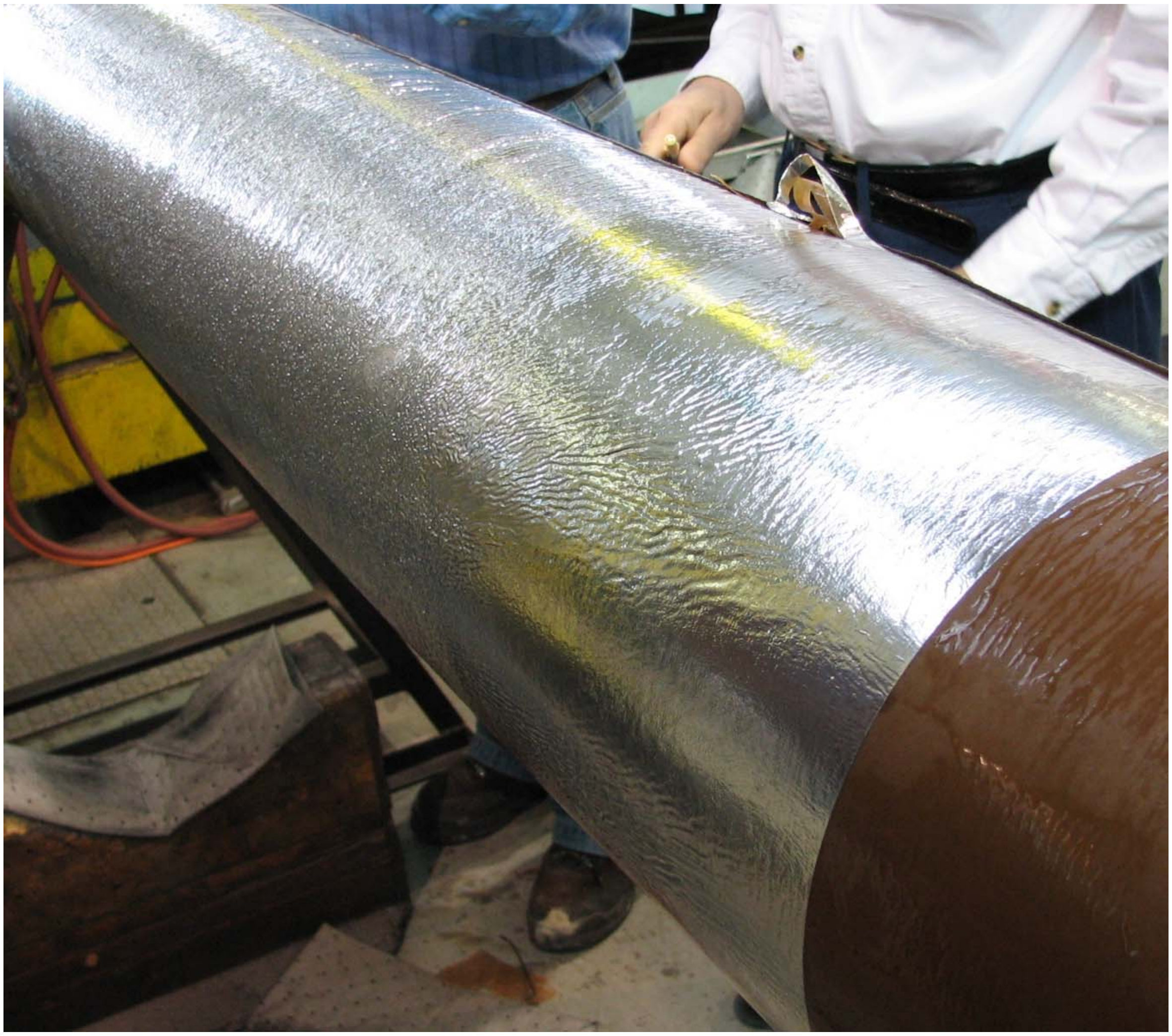
H1 Bushing Core
FIGURE 6

As the paper was unwrapped discoloration was observed on the paper at the foil edge (Figure 7) and conduit used to bring the tapped condenser layer out to the bushing capacitance tap (Figure 8). Minor wrinkles/waves were noted on most foil layers however no abnormality (discharge activity) could be attributed to this particular deficiency (Figure 9).

Discoloration at Foils Edge, H1
FIGURE 7



Discoloration at Tap Layer Interface, H1
FIGURE 8

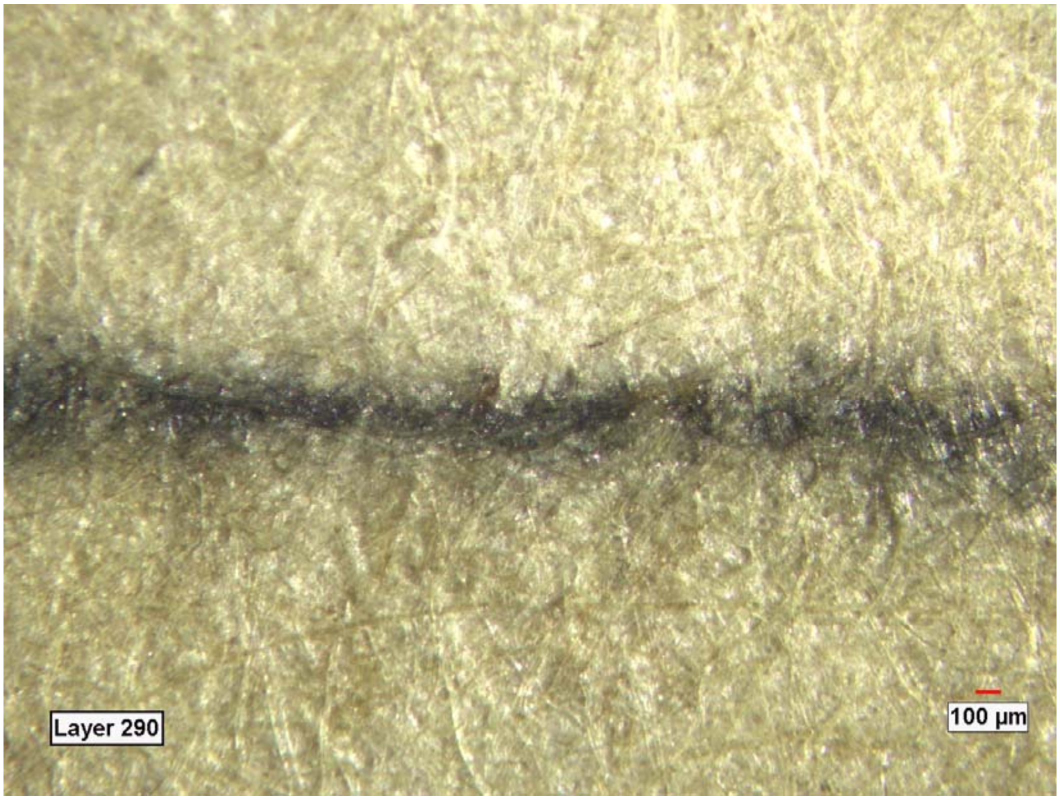


Wrinkled Foil, H1
FIGURE 9

A number of paper and foil samples were submitted to the Doble materials lab for further analysis. A summary of the findings are shown in Table 13. The paper layers are numbered from outer most, (1), to 440, which is the paper wrapped against the center conductor.

TABLE 13
Observations and Findings of the H1Teardown Investigation

LAYER	DP	CAP (pF)	%PF	OBSERVATION
Bumper Shell				Small mass of bluish-green material observed elemental composition titanium, calcium, iron and silicon.
1	713	408	0.07	
24	759	410.4	0.10	Tree like tracking along foil's edge with significant embedded burning. Silver colored fines where foil made contact with paper and also in treeing location. Elemental composition of the treeing area showed carbon at about 56%, oxygen at 43% and copper, sulfur and chlorine at less than 1%. The fines were mainly composed of copper and sulfur indicating possible copper sulfide.
50				Some tree like tracking along foil's edge and area where foil makes contact with paper, silver colored fines along foil's edge
170				Discoloration, result of deposits (no burning), substantial amount of silver fines on paper where foil makes contact
290	992	416.2	0.14	Both deposit and tree like tracking make up the discoloration, left side deposit and right side deposit. No silver color fines on this sample. Elemental composition of the deposits showed carbon and oxygen present but of more interest where the elevated concentrations aluminum, copper and sulfur. Although burning of the paper was most likely occurring, deposition of aluminum, copper and/or their sulfides was the primary reason for the deposition that occurred in this area, see Figure 10.
320Foil				Puncture marks however do not penetrate entirely through foil.
320				Tree like tracking along foil's edge, silver color fines disbursed throughout
360				Combination of electric trees and dark gray deposits make up the dark line about foil's edge. A number of puncture marks however they do not penetrate through the entire layer of paper. Some silver colored fines.
430Foil				Burning of foil's edge caused erosion of foil shown in Figure 11. Melting point of aluminum foil is 660°C.
430				Significant large dark gray deposits, spotty electrical treeing
440	1078	408	0.07	Electrical treeing with large amounts of silver fines (worst of all samples)



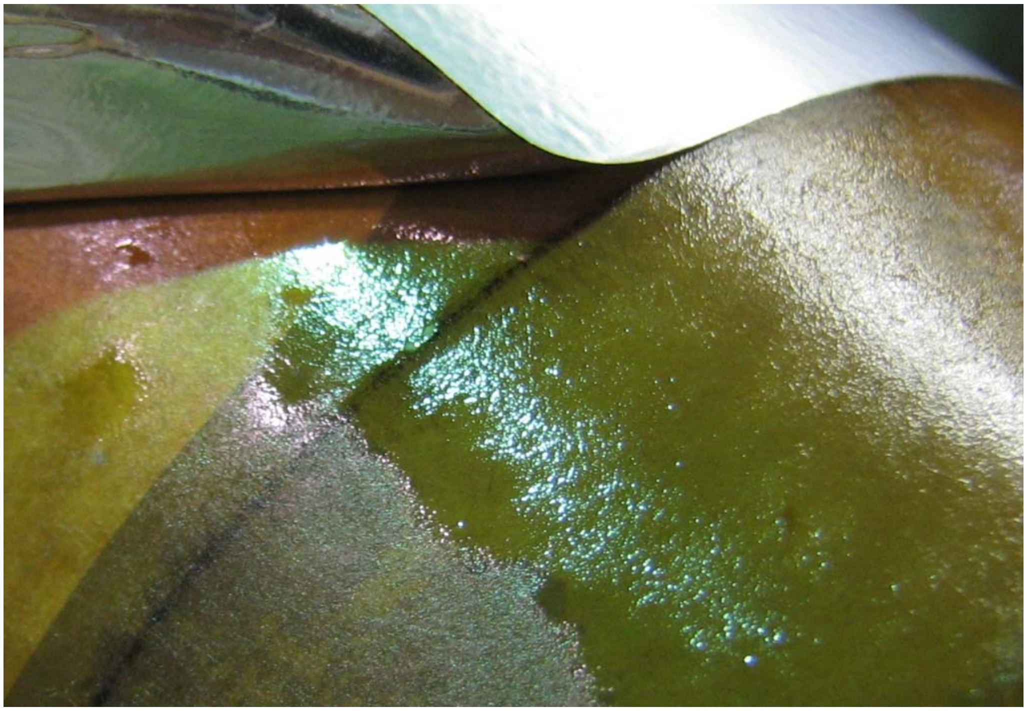
H1, DEPOSIT ON PAPER LAYER 290 MAGNIFIED X66
FIGURE 10

H1, BURNT FOIL EDGE x35 MAGNIFICATION
FIGURE 11

The degree of polymerization (DP) tests suggest some aging of the cellulose material on the outer most layers of the core, however given the vintage of this bushing the numbers are acceptable.

Testing of the oil did not indicate corrosive sulfur. There does not seem to be an abundance of corrosive sulfur in this bushing and it is felt that any production of copper sulfide was secondary in nature and not the reason for the increase in power factor.

The H3 bushing was confirmed to be in good condition through factory electrical testing, which agreed with the results obtained through the on-line monitoring system. However, the disassembly of the bushing seems to indicate early stages of the same phenomenon that affected the H1 bushing. Figure 12 shows one of the discolorations areas along the foil's edge found within H3 bushing that is similar to the ones observed in H1 bushing core



H3, Discoloration Along Foil's Edge
FIGURE 12

CONCLUSION

The degradation rate exhibited by the on-line measurements suggested a long gestation period before failure, which is typical for this type of dielectric medium. One critical factor an on-line monitor cannot predict is future rate of deterioration, which is why ITC Holding Corp made the prudent decision to take an outage at the earliest convenient time. While the on-line data, later confirmed by off-line information, suggested low levels of deterioration there was no way to know how quickly the bushing would degrade going forward, this lead to the decision to proceed with taking the transformer out of service. Knowing there was a distressed asset allowed ITC Holding Corp to anticipate various scenarios; in this situation replacement bushings were located and brought on site prior to taking the transformer out of service.

While it is impossible to predict when the bushing would have failed, both the on-line and off-line measurements indicated that the right decision was made to remove the bushing from service The subsequent dissection of the bushing substantiated the decision to remove the bushing from service, as it revealed deterioration of the core insulation.

It is the belief of the parties involved that failure of this bushing was imminent if it remained in service, resulting in damage to the transformer and its proximity, or possibly a catastrophic transformer failure. By having the on-line monitoring device it allowed for early detection of a possible abnormality, provided a risk management tool, and the facilitation for planning the maintenance to be done on an as needed basis.

BIOGRAPHY:

Robert C. Brusetti, P.E., received his Bachelor of Science in Electrical Engineer degree from the University of Vermont in 1984 and a Masters in Business Administration from Boston College in 1988. He has been employed at Doble Engineering Company for the past sixteen years and currently works in the Client Service department as Product Marketing Manager. Prior to his present responsibility he has held positions as Product Manager and Principal Engineer. Mr. Brusetti is a licensed Professional Engineer in the state of Massachusetts.

Richard F Wancour, P.E., received his Bachelor of Science in Electrical Engineering degree from Wayne State University in 2000 and a Masters of Science in Electrical Engineering degree from Wayne State University in 2002. He has been employed at ITC Holdings Corp since January 2007 and currently works in the Asset Management department as a senior engineer. Prior to his present responsibility he was employed by another utility as a substation design engineer for 6 ½ years. Mr. Wancour is a licensed Professional Engineer in the state of Michigan.

Stephen Molter, has been with ITC Holdings since 2004 as a Senior Engineering Technician. Previously he has work at a southern utility in substations for 27 years and 6 years as a consultant to industrials and various substation maintenance service groups.

Eric Weatherbee, has been with Hubbell Power System's PCORE Electric (previously Lapp Insulator Bushing division) for 18 years working with bushing development, bushing repair and customer service.