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CALIBRATION DIFFICULTIES ASSOCIATED WITH PARTIAL DISCHARGE DETECTORS IN ROTATING MACHINE APPLICATIONS

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Summary

This paper reports the results of an investigation into the factors which can cause difficulties in the objective measurement of partial discharges from machine insulating systems. Results from several motors indicate that the lack of correlation in measured partial dischage levels among different detectors can be explained in terms of detector characteristics ie. input impendance, bandwidth, center frequency, cut-off frequencies.

Introduction

The electrical detection of partial discharges from high power electrical plant insulation affords an attractive method of both monitoring a stress condition which can, in itself, cause severe degradation and possibly failure of plant insulation and provide a basis for estimating the overall integrity of the insulating system since degradation of the system, irrespective of the particular causative stress, almost invariably results in partial discharge activity. In addition, the nature of the discharge pattern with respect to the power cycle voltage e.g. discharge inception voltage, pulse magnitude, symmetry between positive and negative half cycles etc can provide valuable information on the nature of the degradation site and from which its location can, in some circumstances, be inferred[1].

Although many partial discharge detectors have been developed both privately and commercially, they generally operate on the same principle[2]. Although some general recommendations exist concerning the nature of the detector measuring impedance, due to the variable (and often conflicting) requirements of the detector circuit with respect to such factors as resolution, sensitivity etc., there are no specific recommendations concerning its technical specification. In consequence, across the spectrum of partial discharge detectors, there is great variation in such aspects as the magnitude of the measuring impedance and the bandwidth/centre frequency utilized. It might appear superficially than an anomoly exists in this approach (assuming all instruments make comparable measurements) since the signal detected by different instruments from a given partial discharge source would, as a direct result of this variation in detector characteristics, be fundamentally different e.g. the narrowband detector by definition must only detect a small percentage of the total signal of a partial discharge. However, this apparent anomoly is reconciled by injecting a partial discharge simulating calibration pulse into the detector impedance circuit and comparing the response of partial discharges with that from the calibration pulse of known magnitude. Given that the calibration pulse response characteristics are similar to those of partial discharges, then it is argued that the detection circuit, irrespective of the particular processing involved, will respond in the same way to both types of signal and hence the partial discharge pulse magnitude can be inferred [3]. Normally, this is achieved by injecting a fast rise/fall time pulse through a coupling capacitor (C_{cc}) into the measurement circuit. Given that the magnitudes of the pulse (V) and the coupling capacitance (C_{cc}) are known, the response from the detector will be equivalent to an apparent terminal discharge magnitude of Q coulombs where $Q = C_{cc}.V$.

Investigation of Correlation Among Partial Discharge Measurements from Different Detectors

As indicated in the preceding section, although partial discharge detectors have differing measurement characteristics, the results obtained from a given partial discharge source should be comparable irrespective of the particular detector utilized, through the use of the previously described calibration technique. To investigate this assumption, the partial discharge activity of two motors was measured. Firstly, a 6.6 kV motor (with 4 parallels in each phase, 6 coils in each parallel) when energized at 4 kV rms was measured with three different instruments: a commercial Hipotronics corona detector (narrowband - centered on 70 kHz), on Ontario Hydro wideband detector (30 kHz to 10 MHz bandpass), and a commercial quasi-peak meter (narrowband - centered on 5 MHz) normally used with the "TVA" probe. Measurements were made of the complete phase, individual parallels and single coils. Secondly, a 4 kV motor (with 8 parallels in each phase, 5 coils in each parallel) when energized at 3 kV rms was measured for two phases with a commercial detector with three different characteristics (i.e. narrowband at 30 kHz, narrowband at 70 kHz and wideband from 20 kHz to 200 kHz). The individual phases were energized in two ways; (a) with all four terminals connected together and (b) with two terminals connected together and to the high voltage supply and the other two allowed to "float".

Results

A selection of the results obtained are shown tabulated for the 6.6 kV motor in Table 1 and for the 4 kV motor in Table 2.

As can be seen from Tables 1 and 2, there is little or no correlation among the results of the different detectors utilized, irrespective of the part of the winding investigated i.e. phase, parallel or coil. This indicates a weakness in either the standard calibration technique and/or the measurement circuitry. Irrespective of the particular cause however, the effect in relation to diagnostic testing is profound. The lack of an accurate calibration technique means that it is impossible to assign an absolute magnitude to detected discharges. This, in turn makes the assessment of likely void size and rate of discharge degradation impractical since both detector sensitivity cannot be ascertained, any inferences made from the nature of the discharge pattern on the degradation site must be treated with extreme caution. The end result is that a partial discharge can not be used for winding acceptance testing, until an absolute means of determining discharge magnitudes is available. The following describes various tests which allow us to understand why there is a difficulty in measuring winding partial discharges.

	Det.A 70kHz (pC)	Det.B 30kHz-10Mz (pC)	Det.C 5Mz (div)	A/B
Phase A	12000	3000		4.0
Parallel C4	12000	6000		2.0
C3	10000	6000		1.7
B4	12000	8000	28	1.5
B3	8000	6000	21	1.3
B2	8000	6000	15	1.3
A1	7000	5000		1.4
A2	5000	4000		1.2
A4	7000	3000		2.3
Coil C2-1	5500	8000	15	0.7
C2-2	11000	7000	8	1.6
C2-5	5000	3000	6	1.4
C2-6	4000	2000	5	2.0
C1-2	8000	2500	5	3.2
C1-3	16000	5000	7	3.2
C1-4	6000	2000	5	3.0
C1-5	7000	3000	6	2.3
C1-6	3500	2000	4	1.8
C4-1	14000	6000		2.3
C4-2	5000	3000		1.7
C4-3	11000	3000		3.7
C4-4	9000	3500		2.6
C4-5	9000	4000		2.3
C4-6	9000	3000		3.0
C3-1	30000	35000		0.9
C3-2	13000	2000		6.5
C3-3	8000	10000		0.8
C3-4	8000	10000		0.8
C3-5	6000	4000		1.5
C3-6	4000	4000		1.0
B3-1	12000	7000		1.7
B3-2	10000	4000		2.5
B3-3	30000	20000		1.5
B3-4	6000	2000		3.0
B3-5	5000	2500		2.0
B3-6	6000	8000		0.8
B2-1	7000	4000		1.8
B2-2	7000	2500		2.8
B2-3	9000	3000		3.0
B2-4	4000	3000		1.3
B2-5	4000	2000		2.0
B4-1	8000	5000		1.6
B4-2	10000	3000		3.3
B4-3	4000	2500		1.6
B4-4	5000	2000		2.5
B4-5	8000	3000		2.7
B4-6	7000	2000		3.5

Table 1 : Partial Discharge Measurements by Three Detectors in Whole Phase Parallels and Coils

	30 kHz pC	70 kHz pC	20-200 kHz pC	30 kHz-10 MHz pC
Phase A Connection 1	1000	875	390	57
Phase A Connection 2	830	800	305	57
Phase B Connection 1	750	1080	400	57
Phase B Connection 2	875	1160	350	75

Table 2: Partial Discharge Measurements by Four Different Detectors

Investigation of Correlation Among Different Partial Discharge Detectors as Function of Pulse Location

To investigate whether this lack of correlation among the partial discharge measurements from different detectors was pulse location dependant, a partial discharge simulating pulse (essentially similar to standard calibration pulse) was injected at various points along the parallels of three different motors. For one motor, the pulses were injected: (a) near the detector/winding terminals, (b) at the midpoint of the six coil parallel, and (c) at the far end.

For the other two motors, pulses were injected at two locations: (a) the near end (the detector/winding junction) and (b) the far end. In all cases, the responses of the detectors utilized were measured as a function of the calibration/discharge simulating pulse rise time. The detectors utilized variously were 30 kHz narrowband, 70 kHz narrowband, 20 kHz to 200 kHz wideband and 30 kHz to 10 MHz wideband.

Results

As can be seen from Figures 1 to 4, not only is there no correlation among the results of the different detectors utilized at any given pulse injection location but also there is no correlation among the results from different pulse injection locations for any given detector i.e. it might have been expected that the pulse magnitudes obtained from any given detector would follow the relationship with respect to the injection points: Near > Middle > Far, due to the increased attenuation with distance from pulse location to detector[4]. In respect of pulse rise time, as might have been expected, the detectors indicate a decreasing sensitivity with increasing rise time.

The complexity of these responses with respect to pulse location indicates that pulse location is an influential factor in the overall lack of correlation between the results of different detectors. However, the phenomenon is more complex than might have been inferred from the partial discharge measurements alone since the results obtained are contrary to the expected form of attenuation.

Investigation of Effect of Input Impedance and Measurement Bandwidth/Center Frequency on Partial Discharge Response

In addition to pulse location, the other factors which differ among the various partial discharge detectors investigated are their measurement input impedances and selected bandwidths/center frequencies. To investigate the significance of these factors, an experimental program was designed to permit variation of these factors in a controlled fashion. To this end, the detector chosen was not a "commercial" partial discharge detector but a Hewlett Packard Model 8586A Frequency Spectrum Analyser which enabled the display of pulses in the frequency domain over a wide range of controllable bandwidths and center frequencies. In practice, the frequency spectrum investigated was from 10 kHz to 5 MHz in two stages, 10 kHz to 400 kHz and 400 kHz to 5 MHz. In the case of the former, the resolution bandwidth chosen was 3 kHz and, in the case of the latter, 10 kHz. Measurements were made of the peak pulse amplitude from incoming pulses over these frequency ranges. Two input impedances were investigated, a low input impedance of 50Ω, typical of measurement instrumentation, and a high input impedance of 100 kΩ.

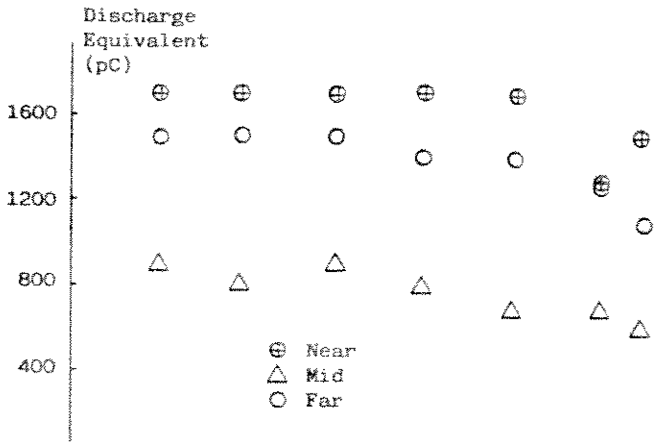

Fig.1: Discharge Equivalent Measurements by 20-200kHz Detector for Various Pulse Injection Locations.

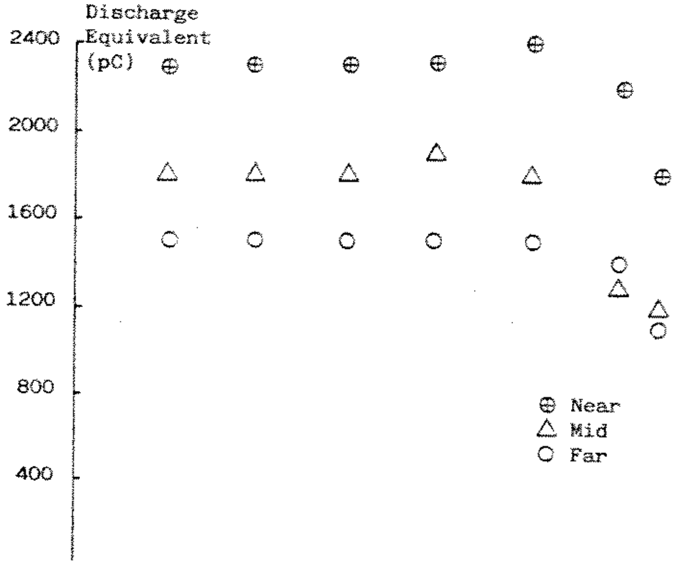

Fig.2: Discharge Equivalent Measurements by 70kHz Detector for Various Pulse Injection Locations.

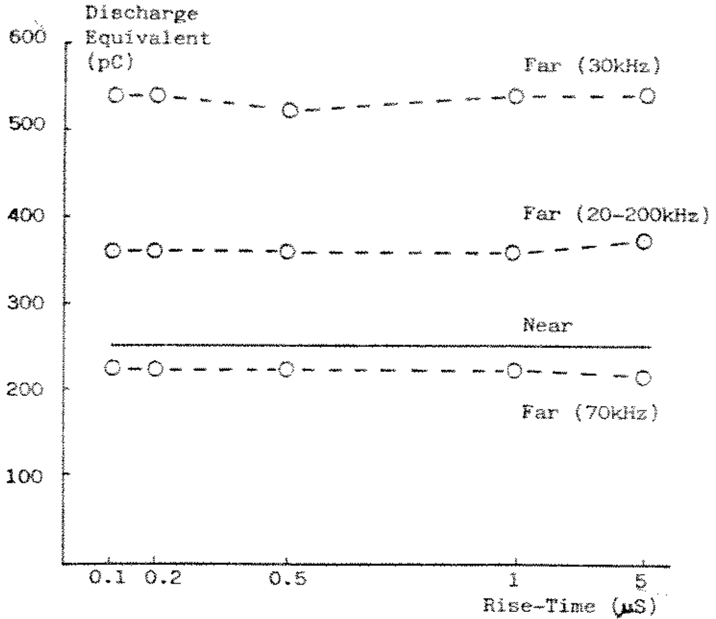

Fig.3: Discharge Equivalent Measurements, Far Terminal relative to Near Terminal Injection for Different Detector Characteristics (Motor B)

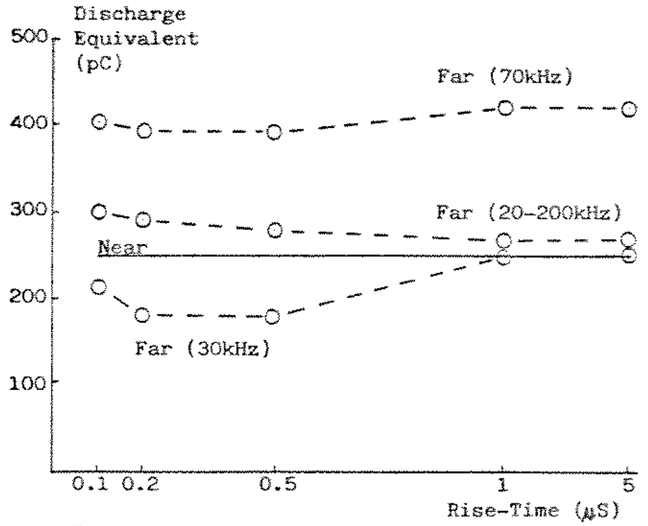

Fig.4: Discharge Equivalent Measurements, Far Terminal Relative to Near Terminal for Different Detector Characteristics (Motor A)

The incoming pulses did not originate from partial discharge sites but rather were simulated partial discharge pulses similar to the calibration pulses detailed in a preceding section. These were injected directly onto the copper at various location points along the length of an isolated parallel comprising six coils, and multiple parallels.
The individual investigations sub-divided into the following sections:

(a) to investigate the effect of the number of connected coils, pulses were alternately injected at one end (N - Near Terminal) and then the other (F - Far Terminal) of a multiple coil series. The detector was always connected to the Near Terminal. The number of coils between the Near and Far Terminals was varied from 1 to 6 (the number in a parallel) and, in turn, the number of connected parallels was varied from 1 to 4 (the number in a phase).

(b) to investigate the effect of partial discharge location, the detector was alternately connected to the Near Terminal and the Far Terminal of a 6 coil series and the point of pulse injection was varied. In practice, pulses were injected at each coil end along the coil series.

(c) to investigate the effect of partial discharge location <u>within</u> a given coil, pulses were injected at various points along a coil in a slot and detected some few coils removed.

(d) to investigate the effect of calibration pulse rise time, pulses of variable rise time between 100 ns and 10 us were injected at the Near Terminal of a 6 coil series and detected at the Far Terminal.

(e) to investigate the effect of detector measuring impedance, procedure (a) was repeated with a 100 kΩ input impedance replacing the 50Ω impedance of (a).

<u>Results</u>
The results obtained are summarized below.

(a) The general type of response obtained from Near and Far Terminals is shown in Figure 5. As the number of coils was varied from 6 to 1, the large peak response was observed to move progressively up in frequency and down in amplitude (Far Terminal response). The observed peak frequencies were, as a function of number of connected coils, 26 kHz (for 6 coils), 33 kHz (for 5 coils), 42 kHz (for 4 coils), 55 kHz (for 3 coils), 73 kHz (for 2 coils) and 156 kHz (for 1 coil). The attenuation was also progressive and produced a maximum variation between 1 coil and 6 coils of approximately x3. The Near Terminal response remained flat across the measured frequency spectrum irrespective of number of connected coils.

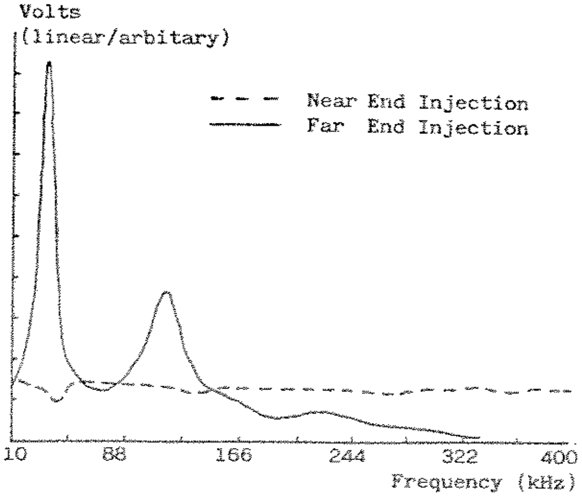

Fig.5: Frequency Response of Discharge Simulating Pulse, Near End Measurement (50Ω).

(b) Varying the pulse location along a 6 coil series also results in a progressive change in the peak frequency and the associated magnitude.

(c) No variation was noted with variation of pulse location in a given coil.

(d) Increasing pulse rise times, as indicated in Figure 6, produced a progressive reduction in the higher frequency components of the pulse spectrum. The effect was noticeable for pulse rise times >3 µs.

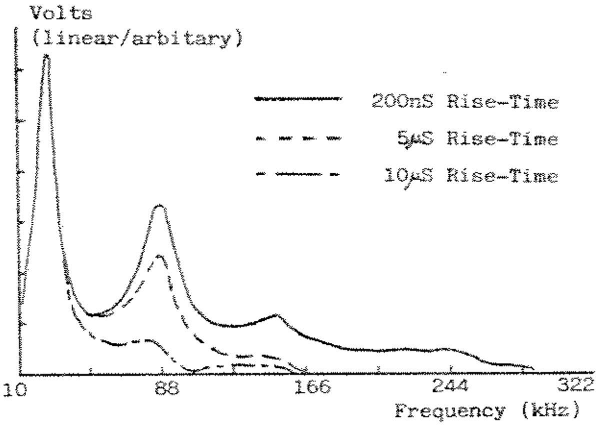

Fig.6: Frequency Response of Discharge Simulating Pulse, Far End Injection, Near End Detection.

(e) The general type of response obtained at the Near and Far Terminals is shown in Figure 7 (6 coil series). As can be seen, unlike (a), both responses are essentially similar. Again, as in (a), the peak moves up progressively in frequency as the number of connected coils is decreased. The amplitude again also decreases but not so significantly as in (a).

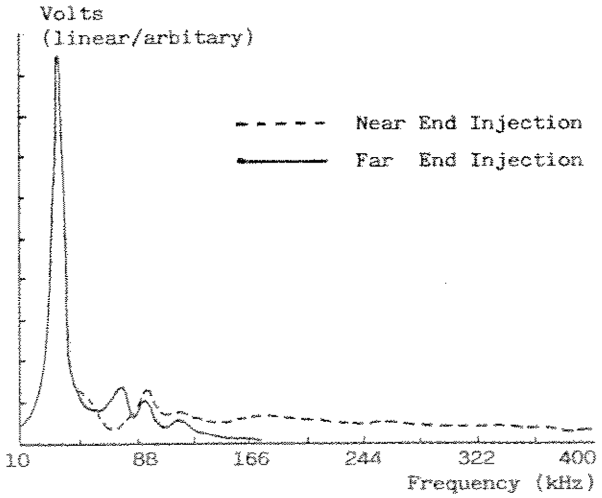

Fig.7: Frequency Response of Discharge Simulating Pulse, Near End Measurement ($100\ k\Omega$)

Discussion

With respect to the results of procedure (a), given that the frequency spectrum analysis is responding in the same way as the individual partial discharge detectors investigated would, this variation in frequency response between the Far Terminal and Near Terminal (calibration pulse) would explain the differing measurements of partial discharge activity from the same source from different detectors (as detailed in Tables 1 and 2). This is best explained by considering Figure 5, and considering the interpretation a variable narrowband detector would place on this result. As can be seen, the calibration pulse (Near Terminal) produces an essentially constant response across the frequency spectrum and hence, irrespective of the center frequency chosen, a narrowband measurement would yield the same discharge magnitude. However, depending on the particular detector frequency "window" of the spectrum chosen, a discharge pulse from a given location might appear significantly larger or smaller with respect to the calibration pulse response. Equally, and again depending on the particular frequency "window" chosen, for a fixed frequency, depending on the domenant frequency of the discharge pulse (i.e., its location relative to the detector) a discharge pulse might again appear significantly larger or smaller than the calibration pulse.

The explanation of this phenomenon lies in the variability of the connected impedance between the partial discharge pulse location and the detector and the resonance phenomena associated with complex LC networks. As the number of connected coils is varied, although this leaves the Near Terminal calibration unaffected, the dominant response frequency increases from approximately 26 kHz for six coils connected to approximately 150 kHz for one coil connected for Far Terminal injection. This is considered to be indicative of a resonant phenomenon for the following reasons. Taking any of these frequencies (irrespective of number of connected coils) and assuming this to be the resonant frequency for that particular number of connected coils and equivalent to the extremely simplified form:

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}}$$

where L and C are the system inductance and capacitance respectively and further considering all of the coils to be similar and hence having similar values of L and C, it is possible to estimate the LC product from the above equation. It is then possible to infer the LC value for any number of connected coils and the associated resonant frequency. On this basis, Table 3 shows a comparison of the dominant frequencies measured for different numbers of connected coils and the resonant frequencies which could be anticipated from calculated LC values. As can be seen, there is reasonable correlation between the two sets of results indicating that the effect is indeed related to resonance within the winding.

Number of Coils	6	5	4	3	2	1
Manual Frequency	26	33	42	55	73	156
Calculated Frequency	--	31	39	52	95	150

Table:3 Resonant Frequencies for Numbers of Connected Coils

That the calibration pulse response (Near Terminal) is small and of constant magnitude can be attributed to the low impedance (50Ω) of the detector which dominates over the effect of the winding impedance and, in consequence, the magnitude is small (since the greater proportion of voltage appears across the calibration capacitance) and of constant magnitude (since, in effect, no resonance can occur).

This phenomenon of variable resonant frequency is not limited to the number of connected coils in the winding. The same type of phenomenon is present as the pulse location is varied. The resonant frequencies are different from the preceding case since the connected impedances are different, but the same type of relationship between the dominant frequencies is again prevalent. This explanation is consistent with that of Wilson et al[5] who also reported resonant effects for a variety of machines.

The increased attenuation with increased resonant frequency is a function of two effects. Firstly, the attenuation in a winding due to the complex nature of the winding impedance and the typical loss mechanisms is greater at higher frequencies. Secondly, the connected impedance between the pulse source and the detector is changing and consequently the overall distribution of voltage changes across the detector measuring impedance. With a low impedance this effect dominates.

This variation in response as a function of pulse location, again assuming comparability between the effect of the Spectrum Analyzer and the various partial discharge detectors investigated, would explain the apparent anomolies in Figures 1 to 4 in which pulses from Far or Mid-winding sources appear larger than Near injected pulses. The explanation lies in the response of a fixed frequency narrowband detector under these conditions. Depending on the pulse location, the resonant frequency will change and if the detector frequency corresponds to any resonant frequency, that pulse will appear larger irrespective of how far it has travelled through the winding.

With respect to high measurement input impedance, as indicated in Figure 7, the response from the Near Terminal and the Far Terminal is essentially the same. Although the resonant frequency shifts as previously, the Near and Far Terminal responses remain essentially similar irrespective of the number of connected coils. In this case, the calibration pulse responds to the connected winding, rather than to the detector input impedance and, in consequence, the responses from the Near and Far Terminals are essentially similar. Obviously, there is still an attenuation in the response as a function of losses and the number of connected coils but this effect is minimized by replacing the low input impedance by a high input impedance.

Finally, as indicated in Figure 6 there is a increasing loss of high frequencies as the calibration pulse rise time is increased (as would be expected) and confirms the results of Figures 1 and 2 which show a decrease in response with increasing rise time irrespective of pulse location.

Conclusions

The conclusions are summarised below. However, due to the limited scope of the investigation to date, these conclusions must be regarded as preliminary and particular to the individual situations of the investigation.

1) Partial discharge pulses are subject to resonance phenomena in a machine winding.

2) The particular resonant response of a partial discharge depends on the location of the discharge in that the dominant frequency peak varies with location.

3) The extent to which a calibration pulse will simulate the response of a partial discharge pulse will depend on the input measuring impedance of the partial discharge detector.

4) The degree of error introduced by the standard calibration technique will vary as a function of the following factors:
   (i) detector input impedance
   (ii) detector bandwidth/center frequency/ cut-off frequencies
   (iii) discharge pulse location
   (iv) calibration pulse rise/fall time
   (v) winding impedance.

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