On-line Partial Discharge Monitoring on MV Motors – Case Studies on Improved Sensitivity Couplers

D. Bertenshaw, M. Sasic.
Adwel International Ltd, Watford, UK and Toronto, Canada.

Abstract - On-line measurement of partial discharge (PD) activity on operating rotating electrical machines has been used for many years as a diagnostic tool for monitoring the condition of stator winding insulation. The progressive development of partial discharge activity is an indication of insulation deterioration. To enable in-service (on-line) PD measurements, capacitive signal couplers are permanently attached to a rotating machine's terminals. The capacitive couplers traditionally used for PD testing on rotating machines have been 80pF. However tests on lower voltage machines (<11kV) have indicated that higher detection sensitivity systems using 500pF couplers can give enhanced PD detection and improve diagnosis capability, potentially improving signal/noise over 80pF.

The first case demonstrates the benefits of the higher sensitivity couplers on a 6.6kV motor where substantial PD signal gain was achieved. The second case showed the different degree to which the PD signature changed between couplers, increasing more at 6kV than 11kV. The third case showed that with 500pF couplers a distinct peak in PD activity on one phase was detected, not seen with 80pF couplers. These demonstrate the benefit of higher capacitance couplers for early PD monitoring on lower voltage machines.

Index Terms - Partial discharge, Couplers, On-line diagnostics, Stator insulation, Motors, Rotating Machines.

1. INTRODUCTION

In-service/on-line PD measurement in generators and motors can monitor the condition of stator insulation without interrupting normal machine service, and has been a recognized tool for predictive maintenance for half a century [1]. It is well known that partial discharge in a machine's insulation can lead to the formation of corrosive chemicals that can further degrade the insulation, an effect that can rapidly escalate. In addition PD can indicate the erosion or damage of semi-conductive coatings due to aging or vibration, and thus be a symptom of other end-of-life aging problems. By regular monitoring and analysis of the PD levels, the rate of degradation can be assessed and corrective or overhaul maintenance planned when convenient, rather than wait for catastrophic failure [2].

A variety of PD measurement instruments and associated Couplers have been developed to implement on-line PD measurement, with 80pF capacitive couplers the most widely used. They are connected via coaxial cables to a termination box mounted outside the rotating machine, as shown in Fig. 1, where the (mV) signals can be recorded by a Partial Discharge Analyser (PDA).

By measuring the PD activity on the machine in service, the insulation condition can be analysed under normal load and temperature conditions, not possible during off-line tests. For this to be beneficial, it is important that the PD system is designed so that the PD signals from the machine are picked up at an early enough stage so that they can be used as advance warning of deterioration, allowing maintenance actions ahead of failure.

2. HISTORICAL PERSPECTIVE OF COUPLERS

The electrical properties, number and connection points of coupling capacitors are determined after evaluating many factors. In the early days (1970s) of on-line PDA technology, the most frequently used coupling capacitor was a cable-type coupler. This was produced by using the capacitance between the core and screen of a specific length of 28kV single core armoured cable.

For temporary installations (performed by hanging the coupler onto the live bus!), 375pF cable couplers were used. The requirement for safe working and creepage distance while operating temporary couplers caused this coupler to be long, hence its higher capacitance. Installation space limited the length of permanently installed couplers to around 1.5m, which resulted in a capacitance of 80pF. This value thus became the norm for PD couplers for many years.

Further development in very low discharge capacitor design led to 80pF epoxy-mica capacitors being introduced in a cylindrical construction. Ease of installation led to their increased use on different machine designs.

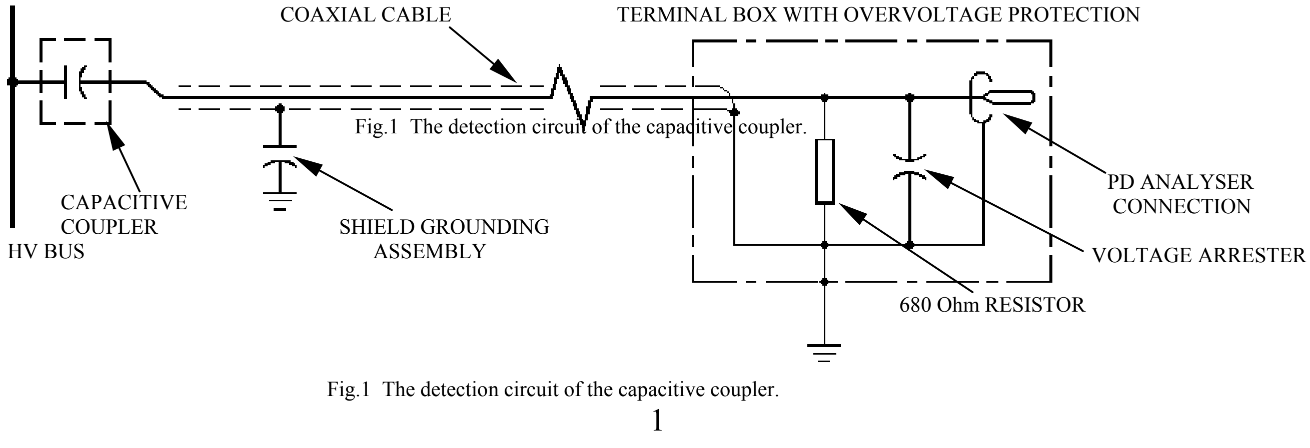

Fig.1 The detection circuit of the capacitive coupler.

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3. COUPLERS FOR MOTORS

However the introduction of epoxy-mica couplers did not change the overall sensitivity of the system. On lower voltage motors it was apparent that the PD levels that are significant were much lower than the levels usually tolerated on HV generators running at 11kV and above. In these motors the insulation is inevitably thinner, and thus has less resilience to PD damage. In addition lower levels of PD can be significantly damaging, thus it is important to be able to measure this lower level PD and reliably discriminate it from noise.

In 1995, epoxy-mica capacitors rated at 500pF and 1000pF and having appropriate HV capability were introduced. These higher capacitance values improved the sensitivity of the PDA system and enabled effective monitoring of lower voltage rated machines. For example, a 6.9kV rated motor monitored using 80pF capacitors did not indicate any PD [9]. Using 500pF capacitors, it was possible to detect PD activity and establish a trend in the early stages of deterioration. If there is any increase in PD activity, the user should have much more time to take corrective action and prevent catastrophic failure.

4. NOISE REDUCTION ON MOTORS

The number of couplers installed in a rotating machine can vary from three (one per phase) up to 24 and more. In directional and differential PD installations (two or more couplers per phase), external noise rejection is based upon matching the timing of signals down the coaxial cable pairs to ensure that pulses coming from outside the machine terminals arrive at the same time at both inputs of the PD Analyser. Such pulses are rejected as being noise.

For a smaller machine connected using high-voltage cables, there is normally insufficient length of bus-bar within or without the machine's termination box to take differential signals from. Thus the installation of just three coupling capacitors per machine is common on machines such as motors and smaller generators. For these PDA installations using a single coupler per phase, noise rejection is based up on a combination of pulse recognition techniques of the PD Analyser, with the pulse attenuation and reshaping characteristics of power cables.

High voltage, solid dielectric cables cause very substantial change of a PD pulse as a result of the large high frequency losses caused by the conductor and cable outer semi-conducting layers and other power cable properties. Pulses are both attenuated and reshaped, and as a result do not preserve sharp rise times along the cable length.

Although of similar design to coaxial communication cables, power cables are designed to carry power at 50 or 60Hz, not high frequency signals like PD pulses. The purpose of the semi-conductive layers (one over the inside, the other over the outside of the cable insulation) is to ensure the whole electric field is concentrated in the insulation. However these layers are resistive, and for frequencies much higher than the designed 50/60Hz absorb signal strength. Further the dielectric properties of the insulation materials used vary over a wide range, and are not optimised for HF signals. Typical cable attenuation at 100MHz is 20db/100m for 28kV XLPE cable and about 35dB/100m for 46kV EPR [3,4], and is higher at higher frequencies. Fig. 2 below shows the effect of such attenuations.

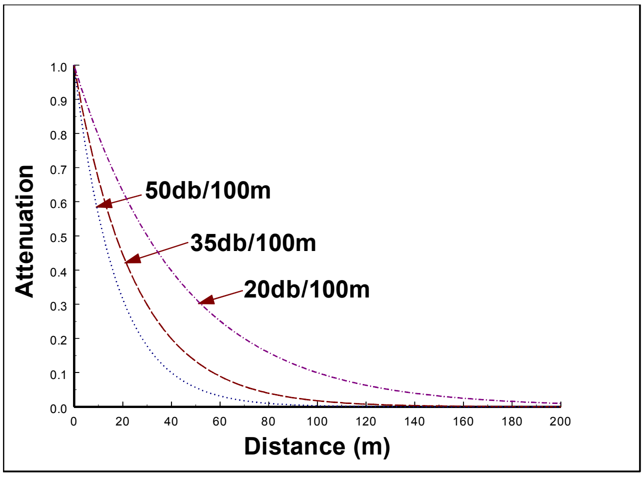

Fig. 2 Attenuation of HF pulses in Power Cable

Thus generally, power cables act as a low-pass filter, and have a tremendous effect on the shape of PD-like noise pulses, widening and reducing the pulse by 20 to 600 times [5,6], since the attenuation is frequency dependant. Cable accessories like splices and terminations further attenuate and reflect PD-like noise pulses coming from possible noise sources connected to the cable.

In addition, power cables are wire or tape shielded and do not pick up radiated noise pulses Therefore use of a single capacitor per phase in PDA installations on cable connected machines will provide both reliable signal collection and rejection of outside noise.

5. PD DETECTION SENSITIVITY, AND FREQUENCY CHARACTERISTICS OF COUPLERS

The frequency bandwidth of a PD detector has a critical effect on PD measurement results. The following factors should be considered for choosing the frequency bandwidth of a capacitive coupler:

(a) the PD and noise frequency characteristics at the detection points, i.e. signal-noise-ratio (SNR).
(b) the frequency characteristics of the machine winding. Very high frequency components of the PD pulse are severely attenuated by the stator winding.
(c) the PD pulse rise-time. PD pulses appearing at the machine terminals, after propagating through the stator winding via a complex L-C transmission path, have lengthened rise-time, and thus less higher frequency components.

The capacitive coupler and the termination circuit constitute the detection circuit, as shown in Fig. 1. The frequency bandwidth of the detection circuit for different capacitance couplers terminated into the 50Ω PD Analyser is calculated and compared in Fig. 3. The LF roll-off (-3db) frequencies are:

80pF = 40MHz,
500pF = 6.4MHz,
1000pF = 3.2MHz

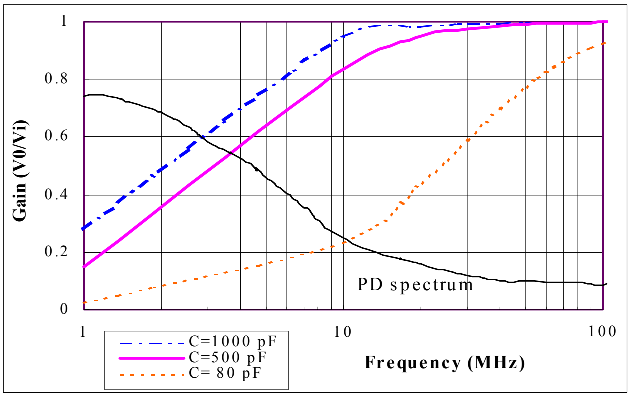

Fig. 3 Frequency characteristics of the detection circuit with various capacitive couplers.

This shows that the higher the capacitance, the wider the frequency band of the PD detection circuit. The profile of the PD frequency spectrum [7] is superimposed on the frequency spectra of the capacitive couplers. The figure indicates that a capacitive coupler with a lower cut-off frequency can detect more PD energy than one with a relatively high cut-off frequency. Hence, increasing the capacitance of a coupler will increase its detection sensitivity by enabling it to operate at relatively lower frequencies and therefore detect more PD signals, thus not worsening its SNR [8].

In addition, there are further issues affecting MV machines. The long winding using coils with thinner insulation inserts a large amount of distributed capacitance and inductance between a PD site deep within the winding and the terminals, considerably more than may be found in a larger HV generator. This acts to particularly attenuate the HF components of the PD signal (effectively widening the pulse) before they reach the terminals and can be measured. This indicates that for such machines the PD detection system should extend its lower frequency limit to maximise detection.

6. COMPARISON OF 80pF AND 500pF COUPLERS ON 6.6kV MOTOR

The following is the results of tests comparing 80pF and 500pF PD Couplers on a working motor on a gas compressor. The test was carried out to demonstrate the proposal that higher value PD couplers have beneficially enhanced sensitivity on lower voltage motors.

A 6.6kV, 10.2MVA asynchronous Motor was connected by 80m of shielded HV cable that provided attenuation of external noise that could appear as PD signal from the motor. The 80pF and 500pF couplers were connected in parallel to each phase as shown in fig. 4. The signals from the couplers were taken back to Termination Boxes and measured using a PDA Analyser.

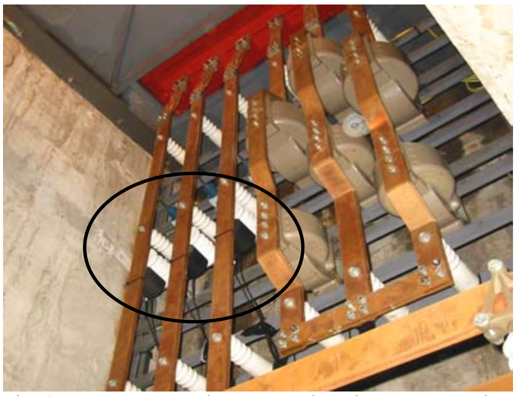

Fig. 4 Temporary couplers mounted on the compressor bus-bars.

The PD signals were measured with the motor in normal operation at 5.4MW load. The PD test results were taken using an Analyser giving full-scale readings of 800mV. The results of all the tests were plotted and the resultant graphs are shown in fig. 5 in a combined form that allows easier comparison.

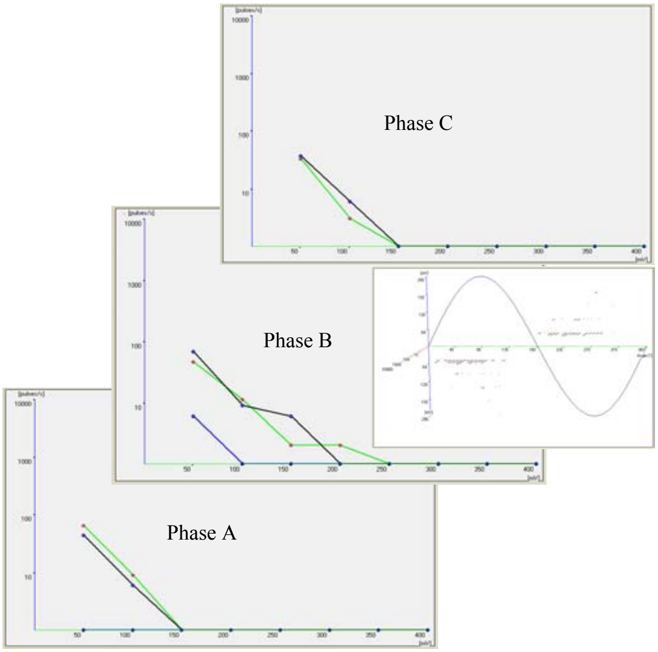

Fig. 5 PD values for 80 vs 500pF couplers at same gain

This shows that for both A and C phases, the 500pF couplers provided a valuable PD signal, whereas the 80pF couplers registered nothing. A phase resolved plot of the 500pF coupler data for the most energetic phase B is inset in fig. 5, showing that the results are not dominated by noise, but by mostly low-level PD that is now being detected.

From the above it can be seen that there is a very valuable increase in PD signal from 80 to 500pF. In addition, the PD seen on the 80pF couplers is so low on two phases that no Qmax value is registered, as the maximum pulse rate is under 10pps. This would preclude trending of this PD signature until the PD level became more intense, loosing valuable analysis history.

7. COMPARISON OF 80pF AND 500pF COUPLERS ON A MOTOR TESTED AT 6KV AND 11KV.

The next case study is a result of tests done on an 11kV, 4.7MW asynchronous motor. This was factory tested (off-load) at both 6kV and 11kV to ascertain the difference in PD results, both with change of coupler capacitance and operating voltage. The PD levels on the machine were known to be high, and already a subject of investigation. Both 80pF and 500pF couplers were temporarily attached and PDA Analyser readings taken.

All couplers were measured at Analyser gains of 2 (normal), 1, 0.5 and 0.25 (max), giving full-scale readings of 800mV, 1600mV, 3200 and 6400mV respectively. The tests were initially made at 6kV then 11kV, in order to determine the degree to which the motor PD was affected by voltage.

The results of the 6/11kV and 80/500pF results for each gain were then laid out graphically to show the distribution of PD values that were occurring. There was no significant change in PD values or signature between the various gains, shown by the graphs falling on top of each other for both 80 and 500pF, as per the 500pF graphs in fig. 6 below.

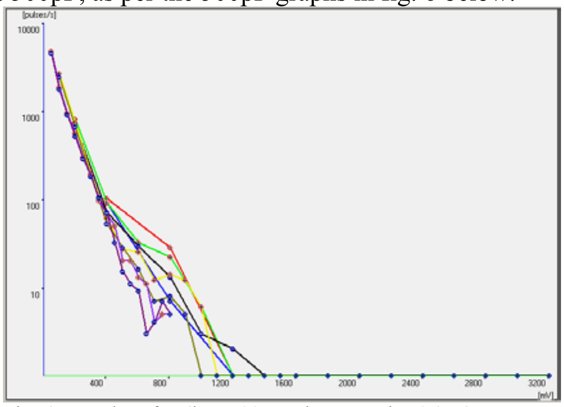

Fig. 6 PD values for 6kV, 500pF, phase B gains 0.25-2.

From this it was determined that the maximum PD values at 11kV/500pF are about 2500mV, thus the gain 0.5 (full scale 3200mV) was chosen for all further comparison. The PD was then compared between 80pF (green/black) and 500pF (red/blue) couplers at both 6kV and 11kV and graphed below in fig. 7 for phase A (phases B and C had similar characteristics).

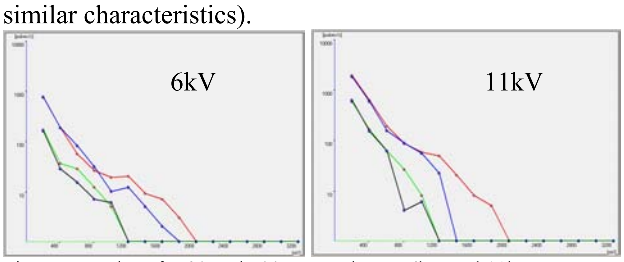

Fig. 7 PD values for 80 and 500pF couplers at 6kV and 11kV.

The PD signal increase (at gain 0.5 = 3200mV max) from 80pF to 500pF couplers was:

Average Qmax increase = 80%

Average NQN increase = 89%

This is typical of the database average increase of 80-100% for -NQN, from 80 to 500pF couplers. However it must be stressed that the database does not contain identical, side-by-side comparisons such as this.

The benefits of using 500pF couplers vs 80pF were more marked at 6kV than 11kV. The relative increases from 80 to 500pF are given in the table below, using values that were aggregated over all phases and +/- PD values.

Voltage	6kV	11kV
Qmax	110%	58%
NQN	107%	78%

The conclusion that can be drawn from this is that the decreasing voltage caused activity deeper in the machine to be more prominent. This is preferentially detected by the 500pF Couplers since they have a lower frequency response to better detect the “deep” PD.

8. COMPARISON OF 80pF AND 500pF COUPLERS ON A 6.6kV PUMP MOTOR.

The following is the results of tests comparing 500pF and 80pF PD Couplers on a 6.6kV, 1.5MW asynchronous motor on a pump in a CO_2 separation plant. The Motor was connected by shielded armoured HV cable >100m long that provided attenuation of external noise which could appear as PD signal from the motor. The couplers were connected temporarily to the motor terminals as in fig. 8 below. The test was carried out to demonstrate the proposal that higher value PD couplers have beneficially enhanced sensitivity on lower voltage motors.

Fig. 8 Motor and temporary coupler connection.

Tests were conducted using PDA Analyser gains of 2 (normal), 4 and 6.25 (max), giving full-scale readings of 800mV, 400mV and 256mV respectively. All couplers were measured at all three above gains with normal connection. The PD signal increase (all gains) from 80pF to 500pF couplers was:

Average +/-Qmax increase =201%

Average +/-NQN increase =156%

This is higher than the database average increase of 80-100%. However it must be stressed that the database does not contain identical, side-by-side comparisons such as this. The range of -NQN numbers for 80pF vs 500pF is from under 100 to up to 2400, so this variation compared to the median increase is not unreasonable for a single statistical sample.

The amount of PD seen from the 80pF couplers was very low at normal analyser gain (2), and only at higher/highest gains (4 - 6.25) could any significant PD be seen. However using 500pF couplers, significant amounts of PD was seen at all normal gains.

The –Qmax levels were compared to the Adwel database for machines with both 80pF and 500pF couplers as in fig. 9 below, and as can be seen this indicates that this machine is in the lower 20-25% quartile of test data. This of course does not guarantee that the machine is not at any risk, but does indicate that urgent attention is not warranted. As always, the best data to use for decisions is from trending a series of tests.

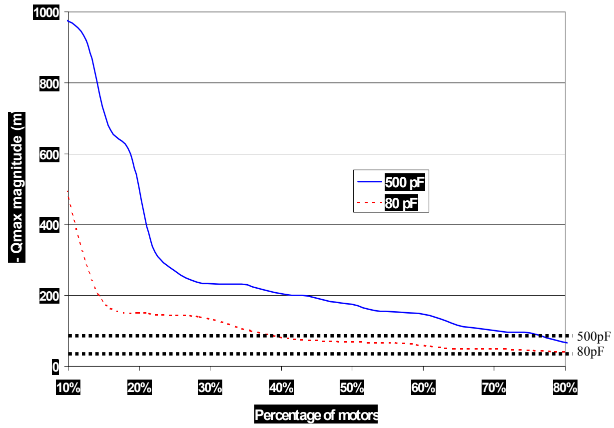

Fig. 9 80 and 500pF –Qmax comparisons with database.

The machine was normally fitted with a "Zorc" surge suppressor. The tests were then repeated with the Zorc disconnected, in order to determine if this either absorbed PD or was a significant source. The result was an overall increase in PD levels of 14%, indicating a slight dampening of PD by the Zorc. This is not sufficient to cause PD measurement problems.

When comparing results between couplers and phases, there was clear evidence of a higher amplitude PD activity in B phase on this machine shown by the 500pF couplers, that was not visible on the 80pF couplers (at any gain). This is shown in fig. 10 below, where the green/black traces are the 500pF and red/blue traces the 80pF.

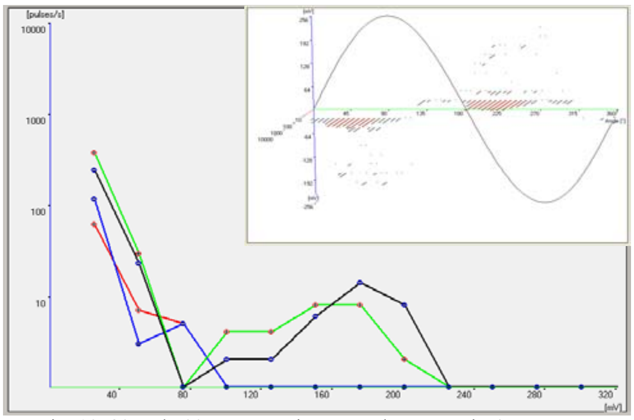

Fig. 10 80 and 500pF comparisons on phase B, gain 4.

In addition a phase resolved plot of the PD on the 500pF coupler is inset, showing that the high amplitude, low repetition frequency PD is not systematic noise, but PD that was otherwise being missed by the 80pF coupler.

This was not evident on any other phase. A separate rise such as this (between 100-200mV) is usually indicative of activity within a particular PD site within the machine. In this case, considering that it was not visible with the 80pF couplers, indicates that the hf components had been particularly attenuated, thus must be quite deep within the machine winding. The 500pF couplers thus give the ability to trend this activity whilst still at an early stage, denied by 80pF couplers.

9. CONCLUSIONS

The above analysis shows that there is a strong theoretical argument for considering higher capacitance PD couplers on lower voltage machines, such a 4-11kV. The results of a number of case studies where it has been possible to conduct side-by-side comparison tests have shown that these benefits are borne out in practice, and enhance the value of on-line PD Analysis as a diagnostic tool for motor insulation condition monitoring. From the cases studied, a good practical choice is 500pF, where valuable sensitivity gains are obtained on machines under 11kV without too great an increase in size. Higher voltage machines (e.g. 13.8kV and above) currently remain best served by the standard 80pF coupler.

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CONTACTS

David Bertenshaw
Director, UK Operations
ADWEL International Ltd
Park House, Greenhill Crescent
Watford, Herts WD18 8PH, UK
Tel (+44) 1923 254433, fax (+44) 1923 218278
Email: dbertenshaw@adwel.co.uk

Mladen Sasic
Engineering Director
ADWEL International Ltd
60 Ironside Crescent, Unit 9
Toronto, Ontario, Canada, M1X 1G4
Tel: (+1) 416 321 1988, fax (+1) 416 321 1991
Email: msasic@adwel.com