Abstract--A new method for assessing the condition of electric contacts and joints inside gas insulated substations (GIS) that overcomes the limitations of conventional diagnostic methods is proposed. The contact resistance in degraded or overstressed electrical contacts varies slightly when currents of different amplitudes are passed. The diagnostic method is based on detecting this non-linear behavior. For testing of the contacts in large GIS, excitation currents up to several thousand amperes are required. By using a capacitor-based current supply, such currents can be achieved with a portable source. The testing can be carried out without dismantling the GIS. No earlier measurements or manufacturer specifications are required. In full-scale testing under realistic operating conditions on 145 – 420 kV GIS using prototype instrumentation a very good sensitivity for detecting contact degradation in an early stage was obtained.

Index terms -- Contacts, Contact resistance, Fault diagnosis, Gas insulated substations, Test Equipment, Testing.

I. INTRODUCTION

It is widely recognized that failure rates for gas insulated substations (GIS) are rather low, but that both outage times and repair costs when serious failures occur tend to be much greater than for air insulated equipment. Thus, substantial efforts have been devoted to quality assurance during design, manufacturing and erection of GIS, and also to developing techniques for condition monitoring of the equipment after it has been put into service.

The majority of the condition monitoring or diagnostic techniques developed particularly for GIS focus on the insulation system. The metal enclosure and small insulation distances of a GIS have brought attention to failure mechanisms that are hardly ever seen in conventional air insulated equipment. For example, a variety of methods for detecting and characterizing moving particles and discharges of various origins exist.

With regard to contact overheating, which is a well-known failure mode occurring in nearly all types of power components, GIS also deserve special treatment. Conventional methods for diagnostic testing of contacts and joints have obvious shortcomings when applied on a GIS. The metal encapsulation that surrounds the conductor precludes an efficient use of infrared imaging systems and also makes the contacts inaccessible for resistance measurements across individual contact interfaces.

Moreover, conventional resistance measurements between bushings, grounding switches or other accessible points of the primary circuit are of limited value because such measurements include many, typically 10 – 30 contact interfaces in series. When measuring a small or moderate resistance increase over such a section it is impossible to determine whether this is due to a large increase in one contact (hazardous), a minor increase in most of the contacts (harmless) or simply that the conductor temperature is higher than during the previous measurement (irrelevant). Thus, when applied on GIS these conventional methods can, at best, only detect a poor contact at a late stage in the degradation process, when a major failure may be imminent.

The extent of contact overheating problems in GIS is not very clear, but cases of severe problems have been reported, also recently [1]. A comprehensive international survey of GIS service experience is available [2], but the failure classifications used do not make it possible to identify those caused by contact degradation. A Japanese investigation dating back to the late 1980s stating that the most serious failure cause for GIS in Japan is poor contacts, is referred to in the literature [3].

Several techniques for detecting contact degradation in GIS have been proposed. These include measurements of mechanical vibrations from the poor contacts [4], gas analyses to detect gas decomposition products caused by contact overheating [5], a magnetic field sensor for detecting poor contacts as changes in the current distribution [3], and a current unbalance alarm scheme [1].

None of these methods have, to the authors’ knowledge, become commercially available, probably at least partly because their sensitivity to detect contact degradation at an early stage is found to be rather poor.

Contact degradation is in many cases a self-accelerated process that after a long period (years) of gradual and slowly
increasing contact resistance escalates rapidly, yielding resistances orders of magnitude greater than the initial value. An appropriate diagnostic method for GIS should be sufficiently sensitive to give warnings long before the contact heating reaches a level where arcing occurs or epoxy insulators disintegrate thermally.

In the present paper a new, non-invasive technique for assessing the condition of contacts in GIS is proposed. Similar to four-point resistance measurements, the method relies on passing electric currents through the section to be tested and record the associated voltage drops. In sections containing degraded contacts certain non-linear and/or irreversible phenomena will occur, indicating that one or more contacts are poor.

Initially, the theoretical basis for the method is presented in some detail. A discussion of important technical matters that have to be resolved in order to build a practical and portable test instrument based on this technique then follows. Finally, a few results obtained during full-scale field-testing using a first prototype instrumentation are presented.

Portions of this work have previously been reported in a conference publication [6].

II. NON-LINEAR RELATIONSHIPS IN DEGRADED CONTACTS

According to the well established understanding of electric contact phenomena [7], [8], an interface between two metallic conductors becomes electrically conducting only where metal-to-metal contact spots are created. Usually, surface asperities, insulating oxide films, contaminations etc. cause this area of true contact to constitute only a small fraction of the apparent contact interface. The associated constricting of the current flow lines gives rise to an electrical resistance, called the constriction resistance. For a circular contact spot the constriction resistance \( R_0 \) is

\[
R_0 = \frac{\rho_0}{2a}
\]

where \( \rho_0 \) is the resistivity of the conductor and \( a \) the radius of the contact spot. Practical contact interfaces contain many contact spots of various sizes and shapes, and the parallel constrictions resistances essentially add up to what is usually referred to as the contact resistance.

When current passes, heat generated by the constricting resistance increase the temperature of the contact spots. For symmetric contacts, it can be shown that the maximum local temperature increase \( \theta \) in the contact spots can be expressed as [9]

\[
\theta = \frac{1}{\sqrt{a^2 + \frac{U^2}{4\alpha \rho_0 \lambda}}} - \frac{1}{\alpha}
\]

where \( U \) is the voltage drop across the contact and \( \lambda \) the thermal conductivity of the conductors (assumed constant). \( \rho_0 \) is here the electrical resistivity of the conductors at an unheated location distant from the contact spots. Resistivity is assumed to increase linearly with increasing temperature \( T \),

\[
\rho(T) = \rho(T_c)[1 + \alpha(T - T_c)]
\]

with \( \alpha \) as the temperature coefficient. Fig. 1 shows a plot of (2) with values of the material parameters as for aluminium. For a given conductor material the temperature rise is solely a function of the voltage drop. Hence, all contact spots in the same interface are at the same temperature.

![Fig. 1. Temperature increase in the contact spots of an aluminium – aluminium contact interface. The bulk temperature of the conductor is 20 °C. \( \lambda = 240 \text{ W/mK}, \rho_o = 2.7 \times 10^8 \text{ Qm}, \alpha = 4 \times 10^{-5} \text{ K}^{-1} \).](image)

As can be seen from Fig. 1, the voltage – temperature relationship is non-linear. A voltage drop of 10 mV yields a temperature increase in the contact spots of only 2 K, while 100 mV causes the temperature to rise 150 K.

Any temperature change in the contacts spots will also change the resistivity of the metal in this region according to (3). This in turn, affects the contact resistance. Thus the contact resistance will take one value for currents so small that only negligible local heating occurs, and a higher value if the currents passed are sufficiently large to cause a substantial local temperature rise.

The ratio between these “hot” and “cold” resistances, denoted \( R \) and \( R_0 \), of a contact can be expressed as [7, p. 78]

\[
\frac{R}{R_0} = \frac{\frac{U}{\sqrt{2\alpha / \rho_0 \lambda}}}{\arctan\left(\frac{U}{2\sqrt{2\alpha / \rho_0 \lambda}}\right)}
\]

where \( \rho_0 \) again is the electrical resistivity distant from the contact spots.

Fig. 2 shows this relationship for a contact between aluminium conductors. For example, at 150 mV the ratio \( R/R_0 \) is approximately 1.5. This means that if a voltage drop of 150 mV is measured across a contact, about 50 mV is expected to be due to the local resistivity increase in the
contact spot region. Using material parameter values for other common conductors, including copper and silver, gives similar results.

![Graph showing voltage drop vs. ratio R/R₀](image)

**Fig. 2.** Ratio between “hot” (I > 0) and “cold” (I ≈ 0) resistance of an aluminium contact calculated from theory (solid line) and measured on a contact between crossed aluminium 5 mm cylinders (broken line). The bulk of the conductors is at room temperature.

Included in Fig. 2 are also measurements of the resistance increase obtained on a contact established simply by crossing two 5 mm solid, circular conductors of aluminium. Currents up to approximately 24 A were applied to obtain voltage drops up to 250 mV.

The effect of the local resistivity increase can also be given as a current – resistance relationship. Introducing (1) and Ohm’s law \( R = U/I \), into (4), yields

\[
\frac{R}{R_0} = \tan \left[ \frac{\alpha \rho_0 I}{\lambda} \frac{1}{4a} \right]
\]

The contact resistance ratio is here given as a function of dimensionless current. Fig. 3 shows this expression calculated for \( I/a \) ratios giving a voltage drop in the range 0 – 250 mV. Results from the measurements on crossed aluminium cylinders that passed currents sufficiently high to cause contact voltages up to 250 mV are also shown.

The effect of local heating of the contact spots is clearly visible in all the curves in Figs. 2 and 3; although somewhat more distinct in those predicted by theory than those found experimentally. However, when taking into account that the theory assumes circular contact spots, that temperature dependencies of resistivity and thermal conductivity are rather simply modeled, and that the contact spot temperature varies between room temperature and almost 600 °C, some deviations have to be anticipated.

Figs. 2 and 3 show that the contact resistance is constant for low voltages and currents but that an increasing resistivity in the contact spots results in an upturn of the curves for higher voltages and currents. Or in other words, a linear relationship exists between current and voltage as long as currents are relatively low. By increasing the current and thereby also the voltage drop, a non-linear regime will sooner or later be reached.

At even higher currents the local temperature in the contact spot may exceed the melting point of the conductor material and local melting will occur. This so-called “melting voltage” is 300, 430 and 370 mV for contacts of aluminium, copper and silver, respectively [7]. Melting alters the contact spot geometries, and will usually cause irreversible changes in the contact resistance; it may increase or decrease significantly.

Since the mass of metal heated by the constriction resistance is minute, the thermal time constant for a contact spot is usually well below 1 ms [7, Chap. 21]. Consequently, the relationships shown in Figs. 2 and 3 are found for all types of current excitation, including ac, dc and pulses, provided that the dominant frequencies are in the kilohertz range or below.

### III. PROPOSED DIAGNOSTIC TECHNIQUE

#### A. Working Principle

The temperature in the contact spots is a good indicator of the quality or condition of a contact. From experience it is recognized that temperature increase and temperature cycling in these tiny areas over prolonged periods of time may have a detrimental effect on the contact. Thermo-mechanical strains and stresses, increased corrosion rates and other degradation mechanisms may then gradually worsen the current carrying ability of the contact spots. As a result, the contact resistance increases, leading to even higher temperatures and further and faster deterioration.

Thus, for power contacts and connectors it is important to ensure that the voltage drop created by the maximum rated load current does not cause 100/120 Hz temperature variations of tens of kelvins or more. For example, the high quality silver plated contacts often used in the conductor joints in a GIS have a nominal contact resistance of typically 5 μΩ. Assuming a maximum rated load current of 3150 A, this yields voltage drops with peak values of 22 mV. If the contact resistance becomes much larger, the local heating is no longer negligible and the long-term stability of the contact can be at risk.
The proposed diagnostic method relies on this correlation between contact spot temperature and the condition of the contact. Excessive contact spot heating is detected as a slightly increasing contact resistance with increasing current, or as irreproducible resistance measurements due to local melting. The test procedure is to pass currents of increasing magnitudes up to the rated load current of the circuit considered, in the present context a GIS section, and accurately determine the resistance each time. If the resistance:

- remains constant for all currents no notable contact spot heating occurs, and all contacts in the considered section are good;
- shows a reproducible increase with increasing currents, the contact spot temperature in one or more contact interfaces in the circuit is substantially higher than the conductor temperature, indicating that one or more of the contacts are deteriorating;
- is irreproducible with significant deviations from one measurement to the next, this is a clear sign of contact spot melting, showing that one or more contacts are severely degraded.

This scheme is generally applicable, but primarily of interest in equipment where the individual contact interfaces are inaccessible for conventional resistance measurements.

The non-linear behavior of poor contacts is well-known and has previously been proposed as a mean for diagnostic testing of other types of contacts, predominantly in equipment with considerably lower ratings [10].

B. General Considerations

A major advantage with this method is that no reference values are required. The interpretation is solely based on comparing resistances obtained with low and high currents, not on earlier measurements, manufacturer specifications or other data that may not be at hand. The method has the potential to disclose whether some contacts in the circuit under consideration are poor, but not which of them.

The sensitivity is essentially determined by the accuracy of the resistance measurements, as well as by the ratio between the resistance of the poor contacts and the total resistance of the examined section.

An instrument for diagnostic testing by this method must contain a current source that can provide excitation currents of different magnitudes, and with a maximum output comparable to the highest rated load current of the equipment being tested. For power equipment currents of several thousand amperes may be required, resulting in a current source of substantial weight and volume.

The approach is to search for small changes in the resistance, not in the inductance or the capacitance. In many circuits the inductive voltage drop may be far greater than the resistive, and this complicates the measurements unless dc excitation is used.

IV. PRACTICAL ASPECTS WHEN APPLIED ON A GIS

A. Connecting the Testing Equipment

The part of the GIS to be examined has to be taken out of service and be accessible in a similar way as when carrying out conventional four-point resistance measurements.

Fig. 4 shows schematically how the excitation current source and voltage probes can be connected to a single-phase section of a GIS. Current is here fed into the primary circuit at an SF₆-to-air bushing, passes through the center conductor and then over to the encapsulation by a grounding switch before it returns to the source through the encapsulation. The voltage probes are connected as close as possible to the section of the primary circuit to be examined.

For GIS without SF₆-to-air bushings or other points where the primary circuit can be directly accessed, all connections have to be made through the grounding switches. Hence, the architecture of the GIS determines what the possible connection points are, and how many measuring sections the GIS has to be divided into. In general, connecting the test equipment is greatly facilitated if the GIS has many grounding switches installed, and especially if these are of the so-called “insulated” type, i.e. with a built-in feature that permits access to the primary circuit without at the same time grounding it.

B. Sensitivity

The sensitivity for detecting poor contacts in a GIS that can be obtained with this method is in the following discussed with basis in numerical examples.

Table I gives typical values for relevant electrical parameters of a single-phase GIS unit. A GIS section with return current through the encapsulation is a largely inductive circuit with a reactance/resistance ratio of around three.

The primary circuit usually consists of a large number of rather short conductor units connected by a male center bolt that is pushed into an annular spring-loaded female contact member of the next conductor unit. A simple rule-of-the-thumb is that the contact resistance in these joints and in switching equipment constitutes typically around half the total resistance in a section. The rest is “bulk” resistance in the
conductors. A typically GIS section on average has around one contact per meter conductor, so the resistance in one contact roughly corresponds to the resistance of one meter conductor.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>TYPICAL PARAMETER VALUES FOR A GIS SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated current</td>
<td>1250 – 4000 A rms</td>
</tr>
<tr>
<td>Conductor resistance</td>
<td>5 – 10 $\mu$Ω/m</td>
</tr>
<tr>
<td>Conductor inductance</td>
<td>0.2 $\mu$H/m</td>
</tr>
<tr>
<td>Conductor impedance</td>
<td>60 $\mu$Ω/m</td>
</tr>
<tr>
<td>Contact resistance per joint</td>
<td>5 – 10 $\mu$Ω</td>
</tr>
</tbody>
</table>

The distance between SF$_6$-to-air bushings, grounding switches and other accessible points for current injection and voltage measurements varies significantly with the architecture of the GIS and with the voltage rating. In a 420 kV GIS it may be more than 20 m from an outdoor SF$_6$-to-air bushing to the nearest grounding switch, while a 145 kV GIS with SF$_6$-to-cable bushings only and many grounding switches can be divided into sections that all are shorter than 10 m.

Consider a rather extreme case with a 40 m long GIS section with a conductor resistance of 5 $\mu$Ω/m that contains 40 contacts, each with a resistance of 5 $\mu$Ω. Thus the total resistance of the section is 400 $\mu$Ω, of which each contact accounts for 1.25% of the total. Assume then that one of these contacts for some reason has deteriorated, so that its “cold” resistance has increased from 5 $\mu$Ω to 25 $\mu$Ω. When passing 4000 A through this section the voltage drop across each of the 39 good contacts is only 20 mV and their contact spots will have approximately the same temperature as the bulk of the conductor. In the last and poor 25 $\mu$Ω contact, on the other hand, contact spot heating will influence the resistivity locally. As a result, when passing 4000 A the contact voltage across this poor contact will be around 150 mV, instead of 100 mV, see Fig. 2. Thus, one third of the voltage drop across this contact originates in resistivity increase due to temperature rise in the contact spots. This current-depending or non-linear part of the resistance constitutes around 3% of the total resistive voltage drop of 1730 mV across the entire section when 4000 A is passed. Consequently, a system capable of measuring resistance to a better accuracy than this, both at low and high currents, will disclose the existence of a poor contact in this 40 m long GIS section.

The non-linear part of the resistance will be significantly smaller in a contact that is less aged and with less than the five-fold resistance increase used in the example above. On the other hand, the resistance of an un-aged contact will not in all cases be as low as 5 $\mu$Ω, and even a doubling or tripling of the resistance may bring the current – resistance relationship well into the non-linear region when currents around the rated load current are passed.

In conclusion, if the resistive part of the voltage drop in a GIS section can be determined with an accuracy of around 1% a very good sensitivity for detecting contact degradation at an early stage is expected.

C. Current Source

The current source should be able to provide excitation currents up to several kiloamperes, but at the same time be portable. These are clearly conflicting demands.

Applying dc greatly simplifies the resistance measurements because various effects related to time-varying currents, such as inductive voltage drops, non-linear phenomena in the iron cores of instrument transformers, magnetic induction and interaction with nearby conductors etc. are avoided. However, dc sources rated for kiloamperes tend to become very bulky and expensive, and dc excitation is for that reason not found to be a viable option.

50/60 Hz ac excitation has also been considered. When applying a pure sinusoidal current to a poor contact local resistivity increase causes the resulting voltage waveform to become distorted with sharper peaks, see Fig. 5. The content of 3rd harmonics increases rapidly with voltage drop, and measurement of the content of 3rd harmonics can thus be used for diagnostic purposes [11].

![Fig. 5. Voltage drop (solid line) over a very poor / overloaded contact when subjected to a sinusoidal current (broken line). These measurements are the same as those presented in Figs. 2 and 3.](image)

However, when applying ac to a GIS the relatively large inductive voltage drop must be taken into consideration, both when rating the power supply and when estimating the accuracy that can be achieved in the resistance measurements. The current source, typically a transformer with a single turn secondary, becomes very heavy, and the resistive part of the voltage drop is to a large extent masked by the much greater inductive voltage drop across the section considered. For these reasons, transformer-based ac excitation is not considered feasible.

The third excitation option that has been evaluated is unipolar current pulses generated by discharging a capacitor bank. The current rating and weight of a capacitor bank are essentially determined by the energy density and the internal resistance of the capacitors used. Furthermore, the amplitude and shape of the discharge current are also determined by the resistance and the inductance of the circuit.

Electrolytic capacitors have very low internal resistance and can thus generate current pulses of large amplitudes when
short-circuited. Their disadvantage is a rather low energy density, which increases the weight of the bank if a current pulse of some duration is required. New capacitor technology, so-called “super-capacitors”, with an energy density typically 100 times greater than conventional electrolytic capacitors is emerging. However, these still have a significantly higher internal resistance than electrolytic capacitors, so in the present application their superior energy density does not bring any weight savings.

In conclusion, a current source based on electrolytic capacitors charged from a 220/110 VAC outlet turns out to be the best solution among the alternatives considered. As will be described in some detail in the next section, a 10 kg capacitor bank charged to 35 V can provide current pulses with peak values up to several thousand amperes and with sufficient duration when discharged through a typical GIS section. However, similar to when using ac, a current pulse causes magnetic induction and other phenomena that complicate the resistance measurements somewhat.

V. PROTOTYPE INSTRUMENTATION

A first, simplified prototype instrumentation based on the requirements outlined above has been built and tested. Overall design features and working principles will be briefly described.

A. Pulsed Current Source

Fig. 6 shows a circuit diagram of the current source, the current leads and the GIS section being measured.

Fig. 6. Simplified diagram of current source and test circuit.

The 4 F capacitor bank is charged to a predetermined voltage using a charger unit supplied from a 220 VAC outlet. When fully charged to 35 V, 2.5 kJ of energy is stored in the capacitors. The energy is discharged through the GIS by firing the thyristor. The resulting current pulse rapidly reaches its maximum amplitude; how fast depends on the circuit parameters, including the capacitance of the bank. When the current pulse is at its peak value the capacitor bank voltage is approximately equal to the resistive voltage drop in the circuit. The current will then start decreasing and dies eventually out, as the capacitor bank is completely discharged.

The bypass diode prevents the capacitors from being damaged by reverse charging, and does also prevent oscillations in the circuit. The air-core coil serves as a current limiter if the terminals of the source are unintentionally short-circuited.

Fig. 7 shows current pulses generated by discharging the capacitor bank through a GIS section. The capacitors have here been charged to approximately 10, 20 and 30 V, respectively, and the resulting peak current values are approximately 1, 2 and 3 kA. The current leads (two 10 m long 70 mm² copper cables) constitute the major part of the resistance in the circuit. Thus, considerably larger currents could be obtained by using shorter leads or by increasing the lead cross-section.

The rise time of the pulses is around 8 ms, which is not too different from mains frequency time constants. For a given circuit, the frequency spectrum of the pulse is virtually independent of the magnitude of the current, giving the same current penetration depths. This is crucially important when the purpose is to carry out accurate resistance measurements of a GIS section at different currents by pulse excitation.

The weight of the capacitor bank is approximately 10 kg. Thyristor, diode, charging unit, air coil, control circuitry (not shown in Fig. 6) etc. bring the weight of the current source up to somewhere between 15 and 20 kg, current leads not included.

B. Resistance Measurement

A standard PC-based data acquisition system is applied. Two differential channels record corresponding current and voltage drop across the GIS section being examined. Current is measured using a Hall-effect open loop current measuring device that gives out a voltage proportional to the magnitude of the current at any time. The sampling rate is 50 kHz and 16 bits analogue-to-digital (A/D) converters are used. Both current and voltage time series are stored as data files.

High frequency noise is removed from these time series by using a finite impulse response (FIR) digital band stop filter with a cut-off frequency of 250 Hz.

Dc-offset in the A/D converters and power frequency noise are removed by taking advantage of the fact that these disturbances are highly predictable. By starting the data acquisition 60 ms (three power cycles) before the thyristor is fired, the periodic noise and dc-offset is measured. These
initial parts of the current and voltage time series are then shifted 60 ms and then simply subtracted from subsequent parts of the time series, i.e. the parts obtained as the pulse current is passed through the GIS. Fig. 8 shows typical current and voltage recordings after filtering.

![Graph](image)

**Fig. 8.** Voltage drop measured across a GIS section (solid line) when a current pulse (broken line) is passed through.

The relationship between voltage drop $u(t)$ and current $i(t)$ across the GIS section is determined by the equation

$$u(t) = R(i,t)\cdot i(t) + L \frac{di(t)}{dt} \quad (6)$$

where $R$ and $L$ are the resistance and inductance, respectively, of the part of the circuit between the voltage probes, see Figs. 4 and 6.

As can be seen from Fig. 8, in the first milliseconds where the derivative of the current is large and positive, the inductive part of voltage drop is significantly greater than the resistive part. When the current has its maximum value, $di/dt$ equals zero and the voltage drop is purely resistive.

The inductance $L$ is the only quantity in (6) that remains constant both during the course of a pulse and between pulses of different amplitudes. Using discrete-time representation and reformulating (6) yields

$$\frac{u(n)}{i(n)} = R(n) + L \frac{i(n+1) - i(n)}{i(n) \Delta t} \quad (7)$$

where $n$ is the sample number and $\Delta t$ the sample interval. The time series $i(n)$ and $u(n)$ are known from the measurements, $\Delta t$ is the inverse of the sampling frequency and $L$ can thus be estimated by linear regression.

Having determined $L$, the inductive part of the voltage drop is calculated and then subtracted from $u(n)$ for all $n$. Then, by the dividing this result with $i(n)$, a time series $R(n)$ being the resistance of the GIS section, is found.

$R(n)$ is however not constant, but differs somewhat throughout the pulse due to variations in the current penetration depth (varying degree of “skin effect”). In order to avoid this source of error, the resistance value from a measurement is always taken as the value found at the same point of the current pulse, namely as the current pulse is at its peak value.

Thus, a section of a GIS is examined by passing current pulses of different magnitudes, and each time calculate the resistance when the current pulse is at its peak value. And, as described earlier, if the resistance varies, this indicates that one or more of the contacts have a too high resistance.

When the current pulse is at its maximum $di/dt$ equals zero, and the inductive voltage drop then becomes zero, according to (6). Hence, the procedures described above for calculating $L$ and subtracting the inductive voltage drop are in principle not required to determine the resistance. By simply dividing voltage drop with current when the current has its maximum value should give the resistance. In practice however, it turns out very difficult to determine at what time the current has its maximum with sufficient accuracy. As Fig. 8 shows, the voltage drops rather rapidly around this point, and a minor error in determining when $di/dt$ equals zero causes a significant error in the resistance value. The applied procedure is considerably more robust.

If the GIS section examined contains instrument transformers with iron cores surrounding the conductor, saturation phenomena in the iron may interfere with the voltage measurements. Such disturbances are avoided by opening the secondary windings of the instrument transformers and installing surge arrestors across their terminals.

Furthermore, in very compact GIS the return current back to the source may take other paths than through the encapsulation of the section being examined. This may induce currents “out of phase” with the current pulse in the center conductor. Hence, these induced currents will not have their maximum at the same time as the injected current, and consequently, they may induce a voltage drop also when $di/dt = 0$ for the pulse. This source of miscalculation is avoided by not using the enclosure as a return path, but instead connecting the current leads directly to the ends of the section being examined. Since this type of induction phenomenon only has been experienced on very compacts GIS, there is no need for extra long current leads to deal with this.

**VI. FULL-SCALE TESTS**

During the development work comprehensive laboratory measurements as well as full-scale tests under realistic conditions on eight GIS installed in 145 kV, 300 kV and 420 kV grids were carried out. A few results will be presented in this section.

Fig. 9 shows resistance values measured on two sections of a 145 kV GIS by applying current pulses with peak values up to around 3 kA. The sections are 5 m and 9 m long, and have a maximum rated load current of 1600 A$_{max}$. Only the bay investigated was taken out of service during the measurements.

The resistances in these two sections are the same for all currents within standard deviations of 0.5% and 0.3%, respectively. Hence the contacts in these sections show no signs of aging.
Fig. 9. Resistance as a function of current for two sections in a 145 kV GIS. The resistances remain constant for all currents showing that there are no poor contacts in these sections.

Similar results were obtained on other GIS, demonstrating that the applied test instruments and procedures make it possible to measure resistance with very good reproducibility and linearity in the rather noisy environment of an energized substation. This is of crucial importance as the sensitivity of this diagnostic method is directly related to the quality of the resistance measurements.

Tests were also carried out on an 8 m long laboratory mock up of a GIS conductor section consisting of two concentric aluminium tubes of 50 and 10 cm diameters. The total resistance of the set-up was increased to approximately 360 $\mu\Omega$ by adding a short stainless steel section. A somewhat poor contact (around 30 $\mu\Omega$) made by partially unscrewing the bolts of a bus-bar joint was inserted in the circuit. Fig. 10 shows resistance plotted as a function of current when twelve current pulses of varying amplitude were passed through this model simulating a GIS section with a poor contact.

Although the poor contact constitutes only around 8% of the overall resistance of the circuit, its non-linear, current-depending fraction is clearly evident as an increasing resistance at high currents. At 3700 A it accounts for only 13 $\mu\Omega$ or 3% of the total, but it is still easily recognized.

Figs. 11 and 12 show some of the measurements obtained on a 420 kV GIS that had been in service for 15 years. The GIS has a full double breaker and double bus arrangement, and only one bus was taken out of service during the measurements. Currents were injected and voltages were measured through the same insulated grounding switches. According to the manufacturer’s representative the grounding switches were equipped with silver plated contacts of the same type as in the disconnector switches in the main circuit.

Fig. 11. Resistance as function of current in a section of a 420 kV GIS. The very poor reproducibility indicates that the resistance in one or more of the contacts is so high that the contact spots melt when the current pulses are passed.

Fig. 12. Part of the resistive voltage recordings obtained from a section of a 420 kV GIS when applying two different current pulses. The inductive voltage drops are removed. The small, abrupt changes in voltage curves are indications of contact spot melting.

The resistances determined in 14 measurements on one section by applying current pulses of peak amplitudes in the range 1–4.5 kA are shown in Fig. 11. This section is rated for 4000 $A_{\text{rms}}$, contains one circuit-breaker, two disconnector switches and several joints, and is approximately 15 m long.

The scatter in resistance values is here nearly 3%, which is one order of magnitude greater than typically found on other
GIS, see for example Fig. 9. Moreover, a systematically increasing resistance with increasing current is not observed. Results with the same poor reproducibility were obtained also on other sections, and it was suggested that the these sections contained one or more contacts with such a high resistance that local melting occurred in the contact spots.

Close examinations of the voltage measurements supported this assumption. Fig. 12 shows two voltage recordings that contain evidence of sudden resistance changes, which is a clear sign of contact spot melting. As outlined earlier, the measurements cannot ascertain whether the poor contact(s) are in the circuit-breaker, disconnecter switches, grounding switches or in the conductor joints. Consequently, further examinations were carried out, including dismantling parts of the GIS to perform resistance measurements across individual contact interfaces.

The outcome of these investigations was somewhat unexpected. First, it turned out that the information given about the contacts in the grounding switches was incorrect. The grounding switches contained only arcing contacts, with no silver plated, low-resistance contacts in parallel. The arcing contacts are primarily designed to be able to withstand arcing, and have a rather high resistance, typically 100 - 200 $\mu$Ω.

Second, an incorrect type of contacting compound (“grease”) had been applied on the main, silver plated contacts in the circuit-breaker during the manufacturing or erection of the GIS. After some years the compound hardened to form a partially solid and insulating barrier that led to a significant increasing resistance with increasing current is not observed. Results with the same poor reproducibility were obtained also on other sections, and it was suggested that the these sections contained one or more contacts with such a high resistance that local melting occurred in the contact spots.

The sensitivity of the diagnostic method is directly related to the accuracy of the resistance measurements. In full-scale testing under realistic operating conditions on 145 – 420 kV GIS using prototype instrumentation a very good sensitivity was obtained.

VIII. REFERENCES


IX. BIOGRAPHIES

Magne Runde was born in Skien, Norway in 1958. He received the M.S. and Dr. Ing. degrees from the Norwegian Institute of Technology in 1984 and 1987, respectively. Since 1988 he has been with SINTEF Energy Research in Trondheim, Norway. From 1996 he also holds an adjunct professor position in high voltage technology at the Norwegian University of Science and Technology. His fields of interest include electric contacts, circuit-breakers, diagnostic testing, and power application of superconductivity. He is presently a member of CIGRÉ Study Committee 13: Switching Equipment.

Odd Lillevik graduated from Department of Electrical Engineering, Norwegian Institute of Technology (NTH) in Trondheim, Norway in 1978. After a short period as a teaching assistant at NTH, he was employed by the Electric Utilities of Oslo in 1979. Since 1980 he has been with SINTEF Energy Research in Trondheim, initially in the Electrical Heating group, and since 1986 in the Power Engineering department.

Vegard Larsen was born in Sotra, Norway, in 1955. He received a M.S. degree from the Department of Electrical Engineering, Norwegian Institute of Technology in 1979. From 1979 to 1985 he was with the Norwegian Electric Power Research Institute (EFI) in Trondheim, where he was working with insulation coordination, transient analyses, and computer software development. From 1985 to 1989 he was with the Norwegian State Oil Company as a Senior Engineer, doing market studies and project planning. Since 1989 Mr. Larsen has been with TransNor, first as Manager for software products, later as President of the company. At present he is Vice President and Sales Manager at TransNor.
Berit Skyberg, born in 1959 received the M.S. degree in electrical engineering from the Norwegian Institute of Technology in 1982. Since 1983 she has been with Statnett, the largest transmission grid company and also transmission system operator (TSO), in Norway. She has been working primarily with planning, design and maintenance of substations.

Asgeir Mjelve was born in Oslo in 1959, and received his B.Sc. degree in Electrical Engineering from Østfold University College in 1980. Since 1982 he has been with Viken Nett, the electricity utility for the city of Oslo and surrounding areas and also the largest distribution grid company in Norway. He has been working primarily with issues related to planning, design and maintenance of substations.

Askjell Tonstad graduated from Department of Electrical Engineering, Norwegian Institute of Technology (NTH) in Trondheim, Norway in 1982. Since then he has been with Sira-Kvina kraftselskap, a major Norwegian producer of hydro power. He has been working primarily with operation and maintenance of power plants and substations, at present in the position as Technical Director.