A PROGRAMME FOR EFFECTIVE RESEARCH INTO SUBSTATION PLANT CONDITION

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INTRODUCTION

The Strategic Technology Programme (STP) operated by EA Technology Limited is described, with particular emphasis on the work of one of the modules, which is concerned with all aspects of substation plant and equipment. The key aims of the STP are to cost effectively improve the operational efficiency and business performance of members within prevailing regulatory constraints. It has proved to be successful in providing solutions for member companies, with outputs generating significant benefits and cost savings. The range of projects undertaken by the substation module over the last 5 years and their application in member companies is discussed, along with the benefits for participating Companies.

BACKGROUND

Following the privatisation of the UK Electricity Supply Industry in 1990 it became more difficult for the individual companies to continue with centrally funded research because of the competition between them, the changes brought about by regulation and heavy constraints imposed on operating expenditure. At the time it was also recognised that much of the previous research had been of a more academic nature and not necessarily focussed on business needs, making it difficult to make a business case to support it. Nevertheless, many of the technical problems remained common to all companies and would benefit from a collaborative approach.

To this end, in 1997 EA Technology created the STP [21] with the objective of providing leading edge technology solutions to cost effectively improve the operational efficiency and business performance of participants within prevailing regulatory constraints.

STRUCTURE AND OPERATION OF THE STP

The STP consists of optional modules devoted to specific areas of research, with a Technology Acquisition Module (TAM) to provide overall direction of the Programme. Participating Companies choose those optional modules that fit their strategic priorities.

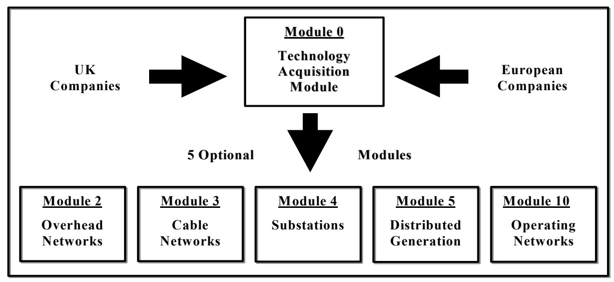

Figure 1. Structure of the Strategic Technology Programme

The strength of the STP concept lies in the fact that projects within the programme are developed by the participants in response to their business needs and are highly focussed on addressing the immediate issues.

The number and structure of the optional modules has evolved, and continues to do so, as the needs of the participants change. The TAM is the base participation module. As well as providing overall direction, the TAM funds projects of a generic or fundamental nature.

Module 2: Overhead Networks addresses present and future options for overhead line development, and the factors which influence the reliability of overhead distribution systems.

Module 3: Cable Networks develops new fault location, cable condition assessment and management techniques.

Module 4: Substations is concerned with all aspects of plant and equipment used in substations, including protection. It is covered in more detail later in the paper.

Module 5: Embedded Generation assists its members to maximise the potential benefits and reduce the costs and risks of network connections at all voltage levels up to 132kV.

Module 10: Operating Networks is directed towards improved customer service and quality of supply, covering; IT systems and network devices to support network management and effective organisation to deal with unplanned events.

Research Project Approval Process

A standard procedure has been adopted for deciding which projects to undertake. Ideas for projects come from the members of the Steering Group and EA Technology. A

Project Proposal is developed which must define the problem or issues to be addressed and identify the scope and tasks. A vital aspect is to define timescales and costs and to identify the benefits for the Module participants. Proposals are presented to the Steering Group at a formal meeting, and members have the opportunity to discuss the content, prior to a vote on their level of support for the proposal.

When a project has been approved a project champion is appointed from the Steering Group, to provide specialist contacts and practical input, to monitor the project progress against timescale, budget and objectives and to assess, discuss and agree conclusions and recommendations.

Project Outputs

All companies participating in a project have full access to the outputs. The intellectual property rights of research outputs are vested with EA Technology,

Whilst the research outputs are confidential to the STP Modules, clearly some projects are of value to others and a Module can decide to offer these for sale. Strict constraints are placed to ensure that confidential and/or commercially sensitive information is not released and IPR is retained.

DRIVERS FOR STUDIES IN SUBSTATION PLANT

Regulatory

The income for Distribution Network Operators (DNOs) in the UK comes from Distribution Use of System charges (DUoS), the transport charge for the movement of energy from suppliers to users through the distribution network. The level of charges that can be imposed by DNOs is determined

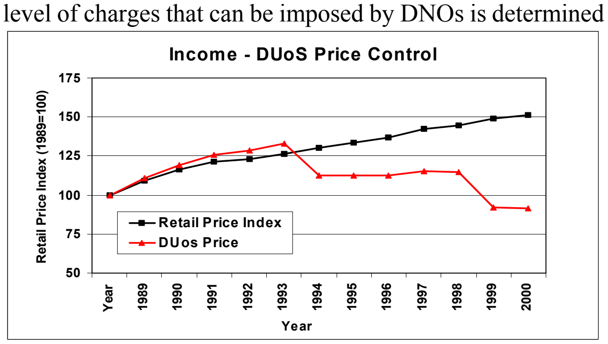

Figure 2. Effect of Distribution Price Control on DUoS Income

by the UK regulator, Ofgem. The effect of the price reviews on one DNO since 1990 [1] is shown in Figure 2. This reduction in income is reflected in all the DNOs and means that all companies must look at how they operate the distributions systems and achieve cost savings with no deterioration in safety standards for operators or the public.

Ageing Assets

The electricity distribution network in the UK underwent a huge expansion in the period 1955 to 1965. A large proportion of plant is now nearly 40 years old. Consequently asset management strategies must take this into account and identify where plant life can be realistically extended thus optimising replacement.

Review of Maintenance Policy

The regulatory and business pressures on operational expenditure have caused all DNOs to review their maintenance activities. At the start of the STP these principally were based on traditional time based maintenance and the processes by which maintenance work actually took place on site had not changed for more than twenty years.

It was evident that a fundamental review of the asset maintenance procedures was required. Many DNOs have adopted Reliability Centred Maintenance (RCM) techniques and methodologies to provide the framework for analysis. However, it was clear that fundamental studies of degradation and failure mechanisms, using both laboratory studies and surveys of in-service condition, were essential to understand more fully the degradation processes.

THE WORK OF STP MODULE 4 (Substations)

The STP Module 4 (STP4) has operated since January 1997 and has been the most consistently supported Module in the STP. Currently all the DNOs in England, Scotland and Wales are represented, providing a high level of leverage of investment in projects by participants.

The purpose of the module is to seek appropriate and cost effective solutions to increase reliability and improve operational, safety and environmental performance of existing and future network substations, including relevant protection and communication equipment. The specific objectives and key issues are reviewed annually and take account of the drivers for research discussed previously.

The following review of some of the wide range of issues and projects covered by STP4 is intended to give an appreciation of the work undertaken. More details can be obtained in [2].

PLANT AND EQUIPMENT ISSUES

Condition of Oil-filled 11kV Distribution Switchgear

An investigation [3,4] was carried out of the condition of older oil-filled switchgear (approximately 30 years) in common use on the distribution network. Data was collected from members on the population of switchgear and representative units were studied in the laboratory to compare the present condition with original material and design specifications. This information was then used to determine an inspection regime and tests were carried on a larger population during on-site routine maintenance.

The general condition of the materials inside the switchgear was very good. The most important factor to prevent degradation of the solid materials in the switchgear tank and to ensure long service life was the cleanliness and condition of the insulating oil. Water ingress (influenced by gasket and vent condition), solid contaminants and metal plating material had a major influence on the quality and condition of the oil. In turn, degraded oil, in combination with moisture and solid contaminants, had a major effect on the condition of the solid insulation in the switchgear and the internal metalwork and surface finishes.

Degradation was found associated with 3 types of metal surface plating finishes commonly found in switchgear:

- Cadmium – this had reacted with oil and moisture to form cadmium soaps (Figure 3), which can lead to electrical degradation of the solid insulation.

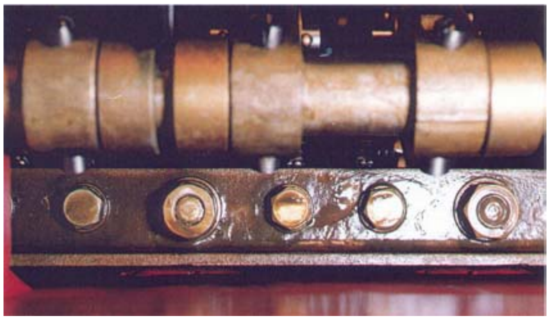

Figure 3. Cadmium rich soap

- Tin - Tin whiskers had grown on the surface of tin plated components (Figure 4). Test indicated they were unlikely to cause breakdown in the oil.

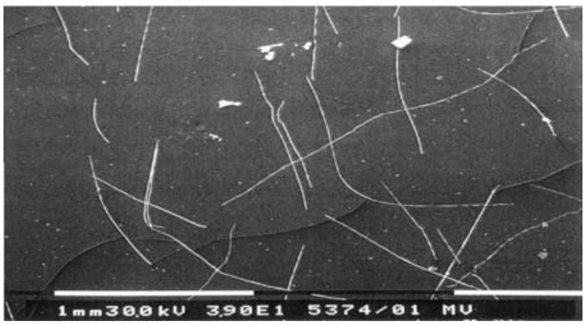

Figure 4. Micrograph of Tin Whiskers

- Phosphated coatings – these can lead to contamination of the oil in wet environments, which may cause degradation of other components.

Cadmium and its components are classified as toxic substances, so further work was carried to assess the health and safety implications. This information was made widely available to allow all UK companies to be aware of the safety issues of handling cadmium soaps.

Gaskets

The gasket materials used in switchgear were subjected to a test regime [5] including hardness, tensile strength, compressibility, fluid resistance and effect on oil oxidation rate before and after ageing. The results enabled direct comparisons of the properties of various types of gasket materials in use. Recommendations were made regarding the correct use, fitting and storage of gaskets.

Solid Insulation in 11kV Oil Filled Switchgear

The relative properties of various types of solid insulation in 11kV switchgear (elephantide, synthetic resin bonded paper (SRBP), glass reinforced plastic (GRP), synthetic moulded composites (SMC) and Permali) were investigated [6]. A correlation was established between the moisture content and the insulation resistance of the materials. A test method was developed using a purpose designed circular electrode system in conjunction with a standard 5kV test instrument to measure the insulation resistance. This method enables the condition of the insulation to be assessed by measuring the surface and bulk insulation resistance and comparing with pass/fail criteria. The electrode system allows the condition of the solid insulation to be determined during routine maintenance.

Sludge in Insulating Oil

In 1996 some failures of oil filled 11kV switchgear were investigated and were found to contain severely degraded oil fitting the general description of sludged oil. Work was undertaken under STP4 [7,8] to identify the source of the problem and the extent of the degradation. Subsequently, further units of switchgear were discovered to contain sludged oil. Because of the relatively large number of sludged switchgear units involved and the potentially serious consequences, additional inspection routines were required to identify sludged units in service. It became clear that a non-invasive method was needed to assess whether sludging had occurred and which could be used with the switchgear energised. It was found that the presence of suspect oil could be detected in the headspace gas, so a method (Figure 5) was devised to extract the gas via the breather orifice, and pass it over a detector.

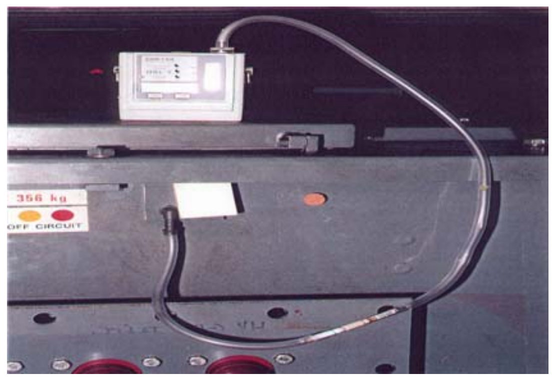

Figure 5. Switchgear head space gas test

Investigations identified which readily available Drager tube gave the most consistent colour change, and the length of the colour change enabled the degree of degradation of the oil to be categorised (Figures 6).

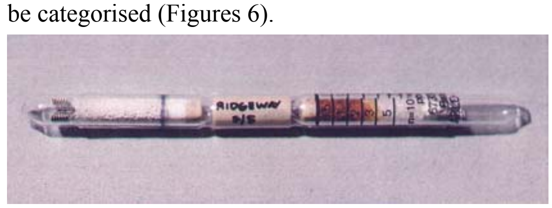

Figure 6. Colour change in Drager Tube – Sludged switchgear oil

The availability of this test enabled the DNOs affected to safely test their equipment, to identify suspect units and to take action before failures occurred.

This concept is being extended to establish a non-invasive method of determining oil condition at all stages of degradation via the headspace gas.

Effects of metals in switchgear on the oxidation of oil

The oxidation stability test for oil involves the use of copper as a catalyst and is particularly relevant to oxidation of oil in transformers. The combination of materials used in 11kV switchgear is more complex and therefore concern was raised that one or more of these materials may be particularly effective catalysts for the oxidation of oil. Accelerated oxidation tests were carried out [8] using as catalysts, a range of different metals that are common in switchgear.

The accelerated oxidation regimes clearly illustrated the high catalytic effect of copper on the oxidation of the oil compared to the other metals – see Figure 7. This confirmed the validity of using copper for the oxidation stability test for oil.

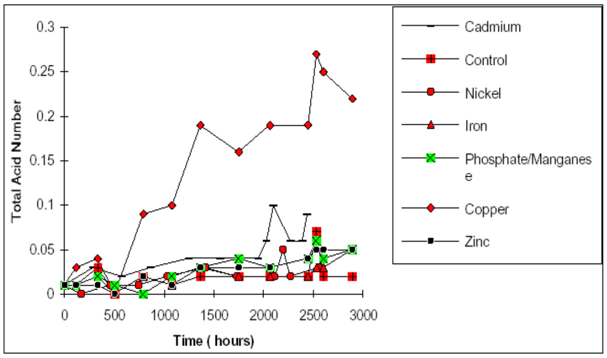

Figure 7. Insulating Oil - The Effects of Metals on Oxidation

Oil condition in 11kV Switchgear

Various projects had established that the condition of oil in 11kV switchgear is the critical factor in determining the need for maintenance. The actual performance of oil in switchgear was studied [9] by collecting and analysing oil condition information from a variety of sources and assessing it against the available knowledge of oil degradation processes. The main conclusions were:

- The condition of switchgear oil at the end of existing maintenance intervals (8 –12 years) was generally good. The effective lifetime of oil in switchgear was therefore greater than the current maintenance intervals.
- The actual effective lifetime of oil in switchgear will be influenced by factors such as detailed maintenance procedures, oil handling practices and general housekeeping associated with maintenance, as well as the combination of materials in different switchgear types. Therefore the effective lifetime of oil will vary for different types of equipment in different companies.
- Oil sampling regimes linked to specific internal inspections offer a viable means of determining the optimum maintenance frequency for switchgear types.

This has allowed DNOs to implement some significant changes to the maintenance strategies and policies for oil switchgear, resulting in considerable cost savings while retaining or even enhancing the reliability of the oil switchgear. This project gave added impetus to the development of techniques for live tank oil sampling [10].

Transformer Management

Of the 132kV and 33kV transformers on UK networks, 75% are over 30 years old. These units are costly to replace, and any deferment of replacement will result in major financial savings to DNOs. A review was made [11] of the various techniques and procedures available to assess the condition and remaining life of power transformers. A framework and options for the on-going management of the transformer population was proposed, covering:

- Oil condition monitoring of transformer / tapchanger
- On-line monitoring systems
- Electrical measurements
- Refurbishment criteria
- Methods of uprating transformers.

This provides member companies with information to assist in developing their strategy for the management of their transformer population.

This work is being extended by using transformers scheduled for scrapping to carry out the available diagnostic tests before decommissioning and to take samples during the scrapping process to establish the true condition of the unit and to correlate predicted with actual condition.

Other Projects

Other projects have been carried out covering areas such as:

- Condition Assessment of Tapchangers.
- Survey of Design and Material Failures in Switchgear.
- Condition of 33kV and 11kV circuit breakers.
- Condition of SF6 switchgear.
- Circuit breaker high-speed mechanism lubrication.
- Issues relating to retrofit circuit breakers.
- Managing the environmental aspects and decontamination procedures for SF_6 filled equipment.
- Assessment of pad-mount distribution substation.
- Asbestos in switchgear and substations.

STRATEGY AND POLICY ISSUES

Maintenance Methodologies

The following areas were covered [12,13,14]:

- Survey of maintenance practices and procedures.
- Available condition based methodologies for optimising maintenance regimes
- Identification of gaps in monitoring techniques.

These projects enabled member companies to assess their own maintenance regimes against others, and provided some of the background information they required to develop future maintenance strategies. The survey is now being repeated to indicate what changes have been made in the subsequent 5 years and the reasons why.

Application of Reliability Centred Maintenance.

The validity of the RCM approach and the effectiveness of different RCM methodologies were studied. 3 companies provided information on RCM studies they had carried out independently on the same type of plant. These were assessed to identify any differences between outcomes. The conclusion was that there was very little difference between the outcomes of the studies, thus giving a high degree of confidence in RCM as applied to electricity network assets.

Plant Defects

Several projects have identified the lack of information available on plant defects that do not involve actual failure. Such data is vital to an understanding of maintenance issues. Whilst a national scheme is operated by the UK Electricity Association (EA) for reporting nationally significant equipment failure and defect reports, this scheme did not cover reports on non-failure defects. STP4 has carried out work to identify the data required to create a suitable database [15,16]. This has resulted in the development of the EA system to include plant defects from early 2002.

Prediction of Asset Condition
The need to understand the condition of plant has gained increasing recognition over recent years. A key requirement is the capability to utilise available asset condition data to predict future changes in asset condition and thereby steer policy decisions. STP4 has demonstrated the applicability of Markov chains [17,18] to provide predictive modelling for electricity distribution assets. Software tools have been developed to assist STP4 members to apply the technique within their own companies. This offers the prospect of optimising maintenance and replacement policies, to both reduce the lifetime costs of asset ownership and to improve safety and operational performance of the network.

Criteria for End of Life Decisions
'End of Life' of plant items is a major issue for DNOs. This project has looked at the question 'what constitutes End of Life for substation assets?' [19] and will provide a means of benchmarking current practices against industry best practice (worldwide). This will enable replacement programmes and capital spending plans to be drawn up in the context of clearly defined and defendable criteria.

Design of earthing arrangements
Design studies [20] have been carried out of earthing designs to limit the potential gradient around pole mounted equipment, with emphasis on adverse soil conditions.

Kelman profile library for 11kV to 33kV circuit breakers
The Kelman Profile P1 is used extensively in the UK for assessing the performance of circuit breaker mechanisms. The objective of this project is to provide a library of profiles for all commonly used circuit breakers to allow quick comparison of profiles and times obtained from particular circuit breaker types.

APPLICATIONS OF STP4 PROJECT OUTPUTS

Much of the work done by STP4 has been used by the participants as the basis for reviews of their maintenance practices. Some of the applications identified by members of the STP4 Steering Group are as follows:

- The work done on RCM methodologies has assisted companies to determine their own course of action.
- Projects researching degradation processes relating to MV switchgear have been used in internal RCM Studies
- The work on gaskets resulted in one company justifying the replacement of gaskets at routine maintenance rather than re-using the old ones.
- Painting policies have been amended following work covering surfaces finishes.
- The research into sludged oil and the development of the head space sampling technique enabled those companies affected to identify affected units quickly, enabling them to control and manage the problems, to lift operational restrictions and also give considerable savings.
- The work on decontamination procedures for SF6 equipment supports and justifies company policies.
- The work on trip and timing tests for circuit breakers has assisted companies to rapidly introduce this procedure.
- Several companies have standardised on the identified best lubricant for high speed circuit breaker mechanisms.
- The outline specification for Pad Mount Substations has been used as the basis for company specifications.
- The use of condition data with End of Life criteria will allow companies to define asset replacement needs.

BENEFITS FOR STP4 MEMBERS

These can be summarised as follows:

- The justification of research budgets can be difficult, but the gearing of 8:1 means expenditure is very cost effective. Research can be undertaken which is beyond the budget of many companies.
- It is an axiom of the STP that all members bring their own company experiences and information to the Module. The quality of the findings depends on a free flow of information to support the researchers, and on open and frank discussions in Steering Group meetings. This has been an outstanding feature of STP4, and has contributed to the success of the projects undertaken. The benefits accrue to both the individuals involved and to their companies.
- The research undertaken is directed by the individual Steering Groups, and the overall programme is managed by the member companies. This means that the research is directed at the issues of most interest and concern to the member companies.
- It has always been the view of STP4 that manufacturers should be involved in relevant projects, and that they receive feedback on the research. This increases the co-operation and information flow for members.
- The research methodology ensures that all projects reflect an industry rather than a company view. This enables companies to use the research outputs to justify their own strategies and policies, confident that they are not in conflict with the rest of the industry.
- RCM has been adopted by most companies as the methodology used to review their maintenance policies and regimes. The work carried out on plant and oil degradation has provided basic information that was not previously available, and has contributed to the successful implementation of RCM.
- STP4 organises seminars covering a group of related topics to communicate the findings, to generate wider discussion and to consider future work. These seminars are free to staff from STP4 member companies.
- Member companies have achieved monetary savings through membership of STP4 because much of the research supports and facilitates in-house developments and decisions as well as allowing direct implementation of a specific technique. The cost of carrying out the research independently would have been prohibitive, and would have substantially delayed the achievement of the benefits noted above. An obvious example is the headspace gas testing for sludged oil, which has enabled several companies to manage the problem, rather than

respond to failures – giving significant safety, operational and monetary benefits.

CONCLUSION

The Strategic Technology Programme has now been in existence for 5 years, and has proven to be very successful in providing research for member companies. It can change to suit the changing requirements of members, as evidenced by the cessation of some Modules and the introduction on new ones. This success has been reinforced by the development of similar programmes in other countries [21].

The format enables several companies to collaborate on problems of mutual interest, without infringing their commercial or competitive concerns. The work carried out by STP4 has provided valuable data that has been used by companies to develop and introduce new techniques and methodologies to improve maintenance strategy, policy and procedures. This is in a large measure due to the past and present members of the Steering Group, who are all enthusiastic in their support and contribution to the Module.

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