Developments in Power System Protection

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Synopsis

Rapid changes are clearly taking place in the field of Power System Protection.

Developments are being both aided and impacted by, amongst other things, the:

- Universal adoption of numerical (electronic/microprocessor-based) protection devices
- Emergence of many novel protection algorithms implemented in software (made possible by the wide-spread acceptance of numerical protection devices)
- Convergence of protection and control into "protection & control devices"
- Development of a truly international standard for substation communications (IEC 61850) - supported by both the US and Europe!
- Implementation of so-called "System Protection Systems" simultaneously monitoring and interacting with network elements that may be very widely dispersed geographically to enhance system stability and reliability
- Necessity for simulators to be able to adequately test advanced protection devices and complex protection systems
- Increasing incidence of embedded generation in networks
- Advances in fault location technologies
- Ubiquitous internet/intranet

This paper looks at some of the international trends now evident in power system protection and provides an broad overview intended more to meet the needs of managers, network engineers, and systems planners and others with general interests in protection, control, and communications, rather than being directed at the dedicated protection specialist.

Introduction

This paper attempts the impossible. That is because it tries to give a broad overview of developments presently taking place in power system protection while so many changes, and so much innovation, is taking place in the protection field.

Consequently this paper can, in reality, only touch lightly on a number of selected issues that seem (to the author) to be - or have the potential to be - significant drivers of the pace and direction of technological change now and in the near future.

This paper is not original. Instead it is a compilation of information from various sources that it is hoped will be of use to non-protection specialists as a broad overview of some the technologies and innovations and, as well, provide some useful references for any readers who may want to find out more about any of the issues it touches on.

The content of the paper is very much influenced by the author's observations and experiences from attending - for the purpose of assessing the present state and future directions of protection technology - the 7th International Conference on "Developments in Power System Protection" held in April 2001. It is also based on further reflections and research on topics of particular interest in the period since that conference.

The International Conference on "Developments in Power System Protection" is conducted at 4-yearly intervals and is organised by The Institute of Electrical Engineers (IEE), UK in association with CIGRE British national Committee, EUREL, IEEE UKRI Section, IEEE Power Engineering Society, IEE Benelux, VDE. The 8th International Conference is scheduled for 2005 (venue yet to be determined).

Numerical protection devices

The numerical protection relay has rapidly taken over earlier electro-mechanical and solid-state analog devices, but even now some manufacturing of protection devices based on these older technologies continues. While numerical relays are almost – but not entirely - universally used in new installations, a large proportion of relays in service throughout the world are still electro-mechanical types.

Evolution

The evolution of protection relays over the history of the electricity supply industry is broadly as illustrated in Figure 1

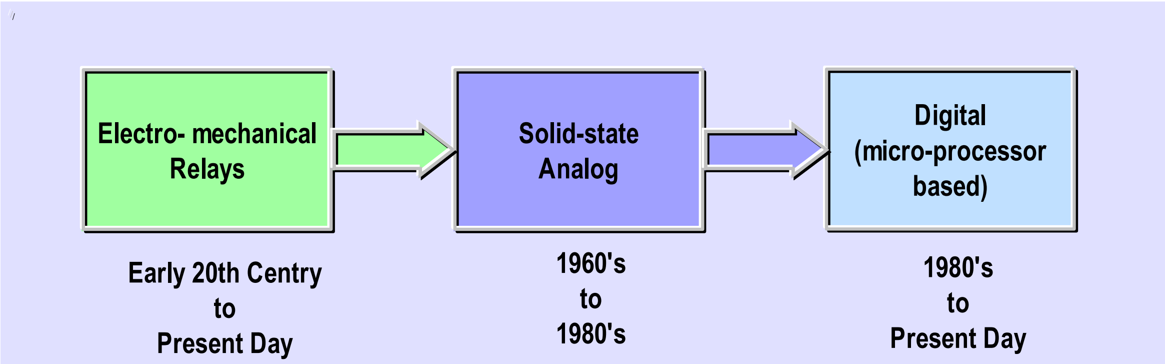

Figure 1: Protection Relay Evolution

Convergence of protection and control

The more recent evolution of the numerical relays has been especially characterised by the convergence of protection relay functionality with other functionality that has formerly been in other stand-alone devices.

This convergence has combined the following functionality

- Protection
- Control
- Metering
- Data Acquisition
- Programmable Logic

into a single unit resulting in what are now increasingly known as either an:

- "**Intelligent Electronic Device**" (IED), or
- "**P&C Substation Nodë**.

Packaged Substations

This convergence of functionality has – amongst other things - facilitated simpler substation designs and contributed to the development of standardised compact substation designs that include all substation components – except transformers – into a single package that can be factory built and pre-tested before delivery to site.

Some utilities report practices that include full testing of all protection and control functions at the place of manufacture – including SCADA system tests (!) - with only full checks of bus-bar insulation integrity and contact resistance on site in conjunction with some other sample repeat tests. By this approach substations are made operational within days of delivery of the packaged substation to site, and overall times from inception to commissioning of just 12 weeks. (Ref 1.)

Business Case Justification for Numerical Relays

There is presently wide discussion in the protection community on the business case justification not only for the adoption of the use on numerical devices, but also for the changeover of existing relays to numerical relays.

Overwhelmingly, the justification is based on the benefits that accrue from the self-monitoring capabilities of numerical devices. These result in both higher reliability and lower routine maintenance costs!!

It is important to note that this justification in NOT based the argument that these devices are inherently more reliable than say, an electro-mechanical relays that have proved to be quite reliable and to have long lifetimes and have served the electricity industry very well. In fact, there is still relatively little known about the actual reliability levels and life-times of modern numerical relays, but during a presentation of a recent paper (Ref. 1) it was stated that "*Electro-mechanical relays are robust devices with long life-times - and that(* in the speakers organisation*) previously the changeover time for relays was 25 years, but is now down to 15 year and becoming less!*".

Rather the argument is that the better reliability arises because these devices can alert operating and maintenance staff that failure has occurred and prompt timely action to remedy the problem. Also this correspondingly reduces the need to carry out routine tests to detect such failures. As has, on the other hand, been the norm with electro-mechanical devices.

Also the basis of the argument is not founded on the equipment costs or maintenance costs themselves, but on the potential savings due to avoided non-supply of power to customers.

Other financial benefits of the application of numerical relays include *"… automation functions that involve breaker operations can be routed through the relay and thus eliminate the need for extra wiring and heavy-duty interposing relays"* (Ref. 2) and this author stated in his presentation that his often uses "*an estimate of (US)$5.00 per foot*[1] *of installed wiring for control and protection panels*".

Universal Relays

Numerical relays provide the foundation on which protection innovation based. The implementation of protection logic into software has opened the door to virtually unlimited opportunities for innovation. Initially this was only to give numerous protection characteristics – including user-defined characteristic curves– but has now extended all types of novel algorithms – for just some examples see the following section of this paper.

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[1] Equivalent to AUS$30 per metre

Numerical relays have now evolved to the point where they have relatively common hardware and are configured for different applications by the software – for algorithms and logic – that is loaded to define its functionality.

Initially this was done the by the manufacturer to create their various offerings to the market, but a logical extension of this approach - that has been taken up by some manufacturers - has been to supply users with a "universal" relay with the actual configuration left to the user.

Novel protection algorithms

The following sections briefly describe some of the innovative and novel protection devices that have been already been applied, or are being evaluated either at a conceptual level or with proto-type devices. Some explanation of the terminology used is also given.

Adaptive Relays:

"Adaptive relays" by definition, employ *"a protective philosophy which permits and seeks to make adjustment to various protection functions in order to make them more attuned to the prevailing power system conditions."* (Ref. 3).

Such relays then may have no pre-determined fixed response, but make decisions to adapt their response according to system conditions – which may include reference to both pre-fault and post-fault conditions.

An example of this approach is a Distance protection scheme in which the relay characteristic is divided into "certain" and "uncertain" regions. The "certain" region is a fixed pre-set region based on system studies for various fault conditions. Faults in the "certain" region are tripped quite quickly, however, for other faults, the adaptive routine is instigated and makes reference to pre-fault system data to help determine its response. It is claimed that improved sensitivity and selectivity is obtained and that "… can improve zone-1 settings up to 95% of the line length (cf. usual 80%) even for high resistance earth faults." (Ref. 4).

"Artificial Neural Networks" and "Artificial Intelligence"

A number of protection applications make use of various pattern recognition or pattern matching algorithms developed for use in other areas of computer science. "Artificial Neural Networks" and "Artificial Intelligence" - often simply referred to be the acronyms "ANN" & "AI" – are examples of these.

A typical example of an application of this type of technology is Distance Protection where pattern recognition techniques are employed to identify faults. Advantages claimed for some such devices is that they can even be "trained" with off-line data. (Ref. 5). See also Ref 6.

Downed Conductor Detection

Some of the most developed advanced protection technology has been applied to detecting downed conductors – especially to deal with the situation where a conductor falls onto ground with high resistivity, or with high resistivity surfaces, possibly at the remote ends of long, high resistance distribution lines.

However, investigation and testing of alternative detection systems is continuing, as it is not considered that the perfect solution has yet been found. A review of the techniques employed is given in Ref 7.

Local Agents

In computer science terms a "Local Agent" is *"a computer program that takes independent action based on events in the surrounding environment"*, (Quoted in Ref. 8). In the power system protection context it refers to a software algorithm that is created to take semi-autonomous action based on its detection of the state of its local environment.

When understood in this context, it may be justifiable to actually include "Local agents" under the "Adaptive Relaying" category described above.

Magnetic Inrush Restraint:

Classic for approach to distinguishing between transformer inrush currents and fault currents has been the use of harmonic restraint based on the ratio of magnitude of 2nd harmonic to fundamental current. New developments are now examining detection methods that instead of using the relative magnitudes of these two currents are based on the phase relationship between the two. (Ref. 9).

Transient Comparison

The availability of high-performance microprocessors in protection devices, yielding fast, low-cost processing of large amounts of data, coupled with optical transducers with high bandwidths has facilitated the introduction of protection devices based on the analysis of fault generated transients.

A description (Ref. 10) of one system employing this technology is a directional relay that relies on the detection of fault generated high frequency current transients and comparisons between the polarities and the spectral energies of the captured transient signals to determine the direction of the fault. It is claimed that the technique is insensitive to fault type, fault position, and fault inception angle and is able to detect lower level and intermittent faults and deal with these and other contingencies noresatisfactorily than conventional techniques.

Wavelets & Wavelet Transforms

Wavelets and wavelet transforms are alternatives the traditional Fourier Transform method of analysing the frequency profile of a signal, especially transients, that attempt to more reliably distinguish between normal and fault conditions e.g. switching onto a faulted line, and switching onto an unloaded line. (Ref 11)

Other

While there are numerous other novel fault detecting methods and algorithms that are being developed, tested and experimented with, one worthy of singling out because of its potential benefits is an over-current relay suitable for operation with measurement CTs using an algorithm apparently immune to the effects saturation that are expected to occur in metering CT when carrying fault currents. (Ref. 12). However, while at the time of presentation of that paper the project reached the "proof of concept" stage, this was only using a MATLAB model of relay.

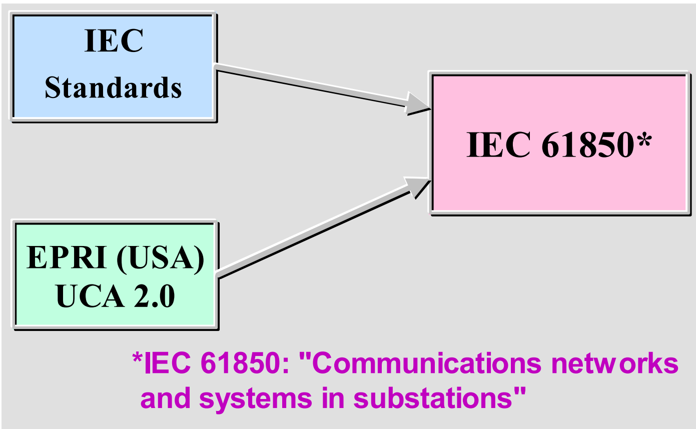
Communications revolution

"The greatest advance in protection in the last 20 years – communications!"

Peter Crossley, Reader in Power Systems, UMIST, UK
Convenor, Developments in Power Systems Protections Conference..

The communications topic attracting great interest in the power systems protection arena is the emerging International Electro-technical Committee (IEC) new international standard for substation communications. Known as IEC 61850: "Communications Networks and Systems in Substations" it is widely considered to be the precursor to new horizons for protection and protection related applications

The IEC 61850 standard is a truly international substations communication standard, involving participation of both Europe and the USA. The new IEC standard is based on the US UCA 2.0 standard and is based the outcome of a cooperative effort.



EPRI sponsored "Utility Communications Architecture" (UCA) that defines object models of field devices and their communications behaviour. Later IEE, EPRI & IEC met and concluded IEC61850 should be based on UCA2 data models and services, but harmonised for international use.

According to a recent paper (Ref. 13) the background story to the standard, briefly stated, is as follows:

> " *EPRI and the IEEE spear-headed an effort to define an Utility Communications Architecture (UCA) beginning in the early 1990s. The initial focus was inter Control Center communications and Substation to Control Center communications. This culminated in the ICCP specification, which was later adopted by the IEC as 61850 TASE.2.*

In 1994, EPRI/IEEE started working on the next phase of UCA – namely UCA 2.0, this time focused on the Station Bus.

In 1996, Technical Committee 57 of the IEC began work on IEC 61850 with a similar charter– defining a Station Bus.

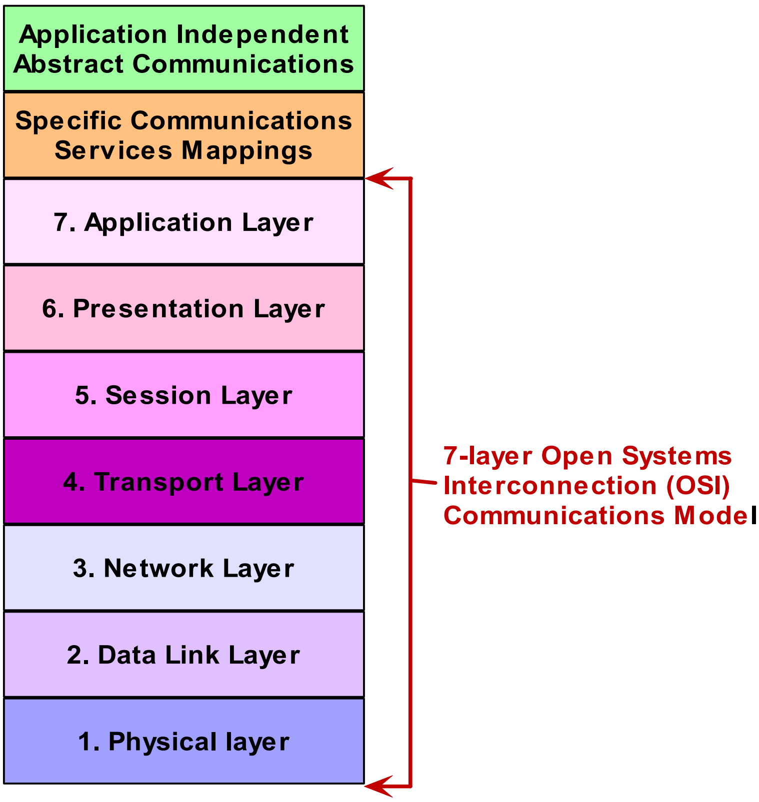
In 1997, the two groups agreed to work together to define a common international standard that would combine the work of both groups. The results of the harmonization efforts are the current IEC 61860 specification.

IEC 61850 is a superset of UCA 2.0, i.e. it contains almost all of the UCA 2.0 specification, plus offers additional features …

According to the current schedule, IEC 61850 will be a published, international standard in 2003."

The differences between UCA and IEC are said to be more in terminology than in fundamental concepts.

The basic architecture of IEC 61850 is the addition of an *Abstract Layer of Generalised Communication* and *Specific Communications Services Mappings* on top of the International Standards Organisation (ISO) Open Systems Interconnection OSI 7-layer communications system model. (This OSI model is the well proven model used by the majority of computer networks today to support open access to network services)



At this highest level, access is obtained completely independently of communications protocols, vendor proprietary communications, the physical medium, etc. by accessing defined software objects that have defined properties and behaviours.

A number of European pilot projects have been used to prove the concepts behind IEC 61850. These include:

- *OCIS:* "Open Communications In Substations" – GERMANY – Jan 98 to Nov 2000. (Ref. 14)

- *PINOCIO:* "Pilot project In the Netherlands for Open CommunicationsI n substatiOns" – Netherlands - EnergieNed, supported by three vendors and an international consulting organisation.

For more information, see Ref 14.

The conclusions from a recent paper (Ref. 15) assert that:

> *"Evidence from these early trial projects suggests that the IEC 61850 standard draft provides a timely, cost-effective, and standardised solution to allow advanced IED functions and distributed systems to form the foundation for 'next generation' electric utility protection, control and monitoring systems. These systems will be highly interoperable, allowing systems to be built, with ease, from products from different vendors."*

System Protection Schemes

Traditionally system protection has been predominantly "local" in nature (eg. under-frequency load shedding). Now – based on communications & accuracy of accurate time-stamping of data from GPS – system-wide protection schemes are being developed.

System Protection Schemes (SPS) have a basic objective "to defend the system integrity during unforseen or extreme contingencies". It is also referred to as "*Distributed Wide Area Protection*" (WAP) or "*Last Ditch Defence*" as such a system is considered as an additional level of protection, designed to initiate the final attempt at stabilizing the power system when a widespread collapse is imminent.

Examples of the application of SPS range from the simple transfer of blocking signals to remote parts of the network, right through to much more sophisticated autonomous systems designed for maintenance of system stability and prevention of cascading tripping and collapse of the system.

The following extract (from Ref 16) details the philosophy and objective of one such SPS:

> "**Philosophy** - to protect against extreme contingencies in that:
>
> 'a wide-spread power failure must not be a consequence of a situation that could reasonably have been avoided'
>
> **Objective**:
>
> 'to preserve integrity … by using automatic measures that are simple, reliable and safe for the system and provide the most extensive coverage against all possible extreme contingencies.'

A conceptual representation of such a system is shown in the following diagram (Figure 2). Note the pivotal place of communications (highlighted) in System-wide Protection Schemes and the use of GPS for accurate time stamping of control data

Examples (detailed in Ref 16):

- Hydro Quebec, Canada

- EDF, France – the EDF Defence Plan includes actions to counteract voltage collapse, frequency collapse, cascade line tripping or loss of synchronism
- Romania

A CIGRE Task Force 38.02.19 produced a technical report on "System Protection Schemes in Power Networks" in 2001 (Ref. 17).

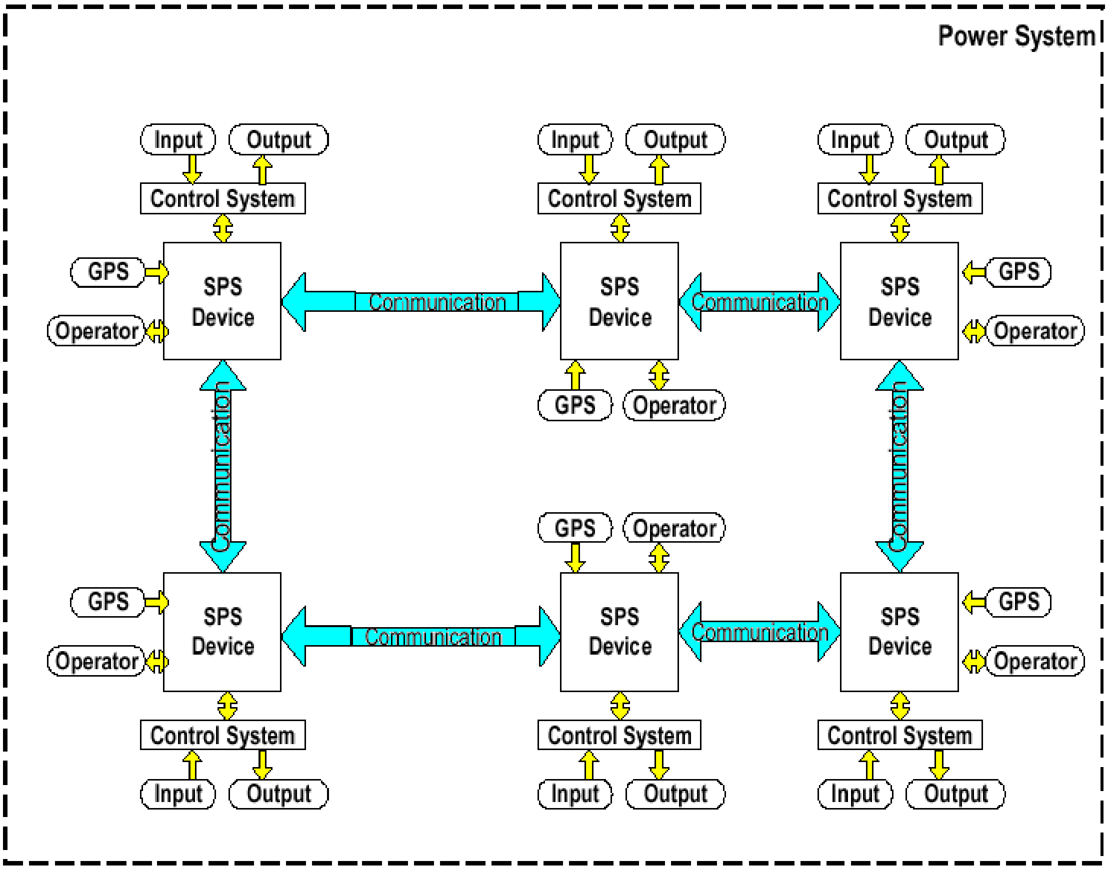


Figure 4. Conceptual representation of SPS (from Ref. 16 – colour highlighting added).

Role of Simulators

Sophistication of protection makes simulators necessary to satisfactorily:

- Test devices of devices and systems
- Determine suitable settings, or evaluate proposed settings

Considerable use is being made of recoded fault data in testing protection systems and devices and in the evaluation of new protection algorithms– especially files in standard COMTRADE (IEEE Standard Common Format for Transient Data Exchange) format for Digital Fault Recorder data (C37.111).

Embedded generation and protection issues

Special issues relating to embedded generation and some of the responses relate to:

- **Islanding** – i.e. separation from grid – typical protection is by detection of Rate of Change of Frequency (ROCOF) and now Comparison of Rate of Change of Frequency (COROCOF) – see Ref. 18.
- **Loss of neutral grounding** -
  Why not have multiple earthing – as in LV systems? (Ref. 19):
  - Unpredictable current sharing
  - Increased ground fault levels
  - Harmonic circulating currents
- **Transients & Nuisance Tripping** - potential for nuisance tripping due to unsymmetrical faults on the grid network, especially with UK protection requirements. (Ref. 20).

Protection and the internet/intranet

Most manufacturers and major utilities have implemented pilot projects. But more is talked about than is actually being done.

Of particular concern is security and deployments of this technology in the near future are much more likely to involve Intranets rather than the Internet. No one is keen to see their protection devices to be seen as a challenge to "hackers" or an avenue for "hackers" to demonstrate their skills.

However, the concept is well proven by pilot projects and some relay manufacturers are already plug-in cards to make IED's nodes with a URL address that allows communication with via Intranet/Internet

Summary & Conclusions

The late 1990's and early 2000's have seen rapid advances take place in Power System Protection technology.

Numerical relays– now more accurately called *Intelligent Electronic Devices* (IED's) - with algorithms implemented in software means that almost "anything is possible". This has enabled considerable experimentation and evaluation of novel protection algorithms many of which show great promise in making more accurate determinations of if fault conditions exist and, if so, establishing with greater precision the nature and whereabouts of the fault (or faults).

The emerging new communications standards (IEC 61850) together with the "open-systems" type of access they will support will undoubtedly herald a whole new wave of innovation in protection.

Communications developments are also underpinning some very significant system-wide protection schemes designed to avert widespread and chaotic dislocation of inter-connected power systems. The ease of access to accurate signals from GPS for time stamping data makes a new level of intelligence to be applied in pursuit of system security through the use of so-called "Wide Area Protection" (WAP).

By the time the next International Conference on "*Developments in Power System Protection"* takes place in 2005 some significant shifts can be expected to have occurred in the electrical protection landscape. Some technologies that now in their early stages of development will undoubtedly have become firmly established as accepted solutions. Meanwhile, some will have faded away, while others, not yet even on the radar, will undoubtedly have emerged as superior solutions to already recognised or new protection problems.

Developments are taking place so rapidly that even the dedicated protection specialists find it hard to keep up with developments in their field – especially since there are now so few of them and their workload is onerous – and for those with a more general interest, or need to know, they find it doubly difficult. It is for this latter group that it is hoped that this paper will contribute towards keeping them abreast of present developments … at least to some degree!

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