Lowering the Cost of Small Hydro Protection and Control through Tailored Algorithms and Simulations Optimized for Low-cost Microcomputers

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Abstract

With the growing interest in resurrecting and refurbishing many small hydro plants both nationally and internationally, often in remote areas, solutions to the problems of high hardware costs and increasing need for high level technical personnel has been sought.

The past decade has witnessed a significant fall in the cost of high-speed microcomputers with a substantial increase in their computational speed. Combined with the availability of effective high-level software development tools, this has allowed for the introduction of these low cost devices in new applications whilst augmenting functionality.

This provides an opportunity for the hydro protection and control industry. Integrated platforms consisting of lower cost, application specific electronic modules, capable of providing enhanced functionality combined with customer configuration options are gaining favor with many hydro plant owners, particularly those with small sites (< 10MW).

In order to realize this opportunity, two challenges must be met: firstly, how to obtain the fast computation times required for the full complement of control and protection functions in individual low-cost microcomputers; and secondly, how to establish a low-cost environment for enabling the development and verification of the various algorithms.

The increased speed provided by tailored algorithms has enabled the capability for multifunctional protection using a low-cost state-of-the-art microcomputer facility. Excel with Visual Basic for Applications on an everyday PC was found to be an effective low-cost environment for the development and testing of small hydro protection and control algorithms. The techniques developed and utilized show that the latest generation of low-cost microcomputer can be employed as an integrated platform for small hydro protection and control, offering the added benefit of an integrated facility for customer configuration.

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1 Introduction

The past decade has witnessed a significant fall in the cost of high-speed microprocessors and a substantial increase in their computational speed. Devices designed to handle multiple-input multiple-output configurations, such as for the automotive, consumer electronics and small-scale industrial controls industries have opened doors for application specific uses where none have existed previously. Combined with the availability of effective high-level software development tools, this has allowed for the introduction of these low cost devices in new applications whilst augmenting functionality [1].

A concern from utilities when interconnecting with smaller generators is the protection of their networks from generator faults. At times this has resulted in small hydro producers expected to bear prohibitive interconnection costs including a requirement for technical knowledge well beyond their normal resources. A similar concern exists with the producers themselves as they seek to strike a balance between the protection of their generating equipment and the cost of the systems required for protection and control. With the growing interest in resurrecting and refurbishing many small hydro plants both nationally and internationally, often in remote areas, solutions to the problems of high hardware costs and increasing need for high level technical personnel has been sought.

These trends offer an opportunity for the hydro protection and control industry. Integrated platforms consisting of lower cost, application specific electronic modules, capable of providing enhanced functionality when combined with customer configuration options are gaining favor with many hydro plant owners, particularly those with small sites (< 10MW). In developing countries where the access to adequate hardware is frequently limited due to cost or technical complexity, the use of low cost devices combined with user friendly configuration software is enabling increased generation capacity, enhanced reliability and more cost effective installations.

In order to realize this opportunity, two challenges must be met: firstly, how to obtain the fast computation times required for the full complement of control and protection functionality in single low-cost microcomputers; and secondly, how to establish a low-cost environment for the development and verification of the various algorithms.

2 Tailored Algorithms for Fast Computation

A single multi-functional protection module must perform a large number of tests in a regular and timely manner. Starting from the full range of protections considered appropriate for a small hydro installation (<10MW)[2], it was noted that the processing load falls mainly into two areas:

- calculation of derived quantities (r.m.s. voltages and currents, powers, third harmonic voltage magnitude, frequency, r.m.s. differential current, negative sequence current)
- protective checks - generally a comparison between a derived quantity and a threshold value

With a state-of-the-art 16-bit microcomputer, initial consideration was given to using the built-in floating point arithmetic routines. It rapidly became apparent that the computational time associated with these would make the system unviable. Recourse was thus made to fixed-point scaled-fraction arithmetic, in which all variables are scaled in the range (-1,+1). Thus, using 16-bit signed integers:

[value / scaling factor] = [scaled fraction value]
[scaled fraction value] * 32768 = [16-bit signed integer value]

With this approach, the scaled fraction values range between –1.00000 and 0.99997, corresponding to signed integers ranging between –32768 and +32767.

This required the preparation of efficient fixed-point arithmetic routines tailored for scaled fraction operation. The table below compares the times associated with the floating point and fixed-point operations.

	Floating Point Built-In (μs)	Scaled Fraction Fixed Point (μs)
Add, Subtract	12-14	0.5-0.9
Multiply	12	1.4
Divide	40	2.5
Comparison	3	0.5-0.8

Though this improvement was dramatic and sufficient for the comparison part of the protective checks, it was still necessary to establish fast and accurate algorithms for the derived variables. The next sections consider this aspect.

2.1 R.M.S. Voltages and Currents

R.M.S. voltages and currents are key parameters for monitoring and protection. However, even with the use of scaled fraction fixed-point arithmetic, the computational times required for square rooting (a necessary part of the r.m.s. calculation) were considered too high. It was therefore decided to look at other options:

- avoid the need to take square roots (i.e. either through approximate algorithms or working with mean-square values)
- develop a fast square-rooting algorithm tailored for 16-bit fixed-point scaled fraction arithmetic.

Following the latter option, a new algorithm for fast square-rooting tailored for scaled fraction arithmetic was developed. Its times are compared below:

Square Root Algorithm	Time (μs)
Built-in floating point	210
Tailored fixed point	15

Results confirmed that the new tailored algorithm is within 1-bit (0.00003) of results obtained using the library Excel / VBA integer square root algorithm over the full range (0,1).

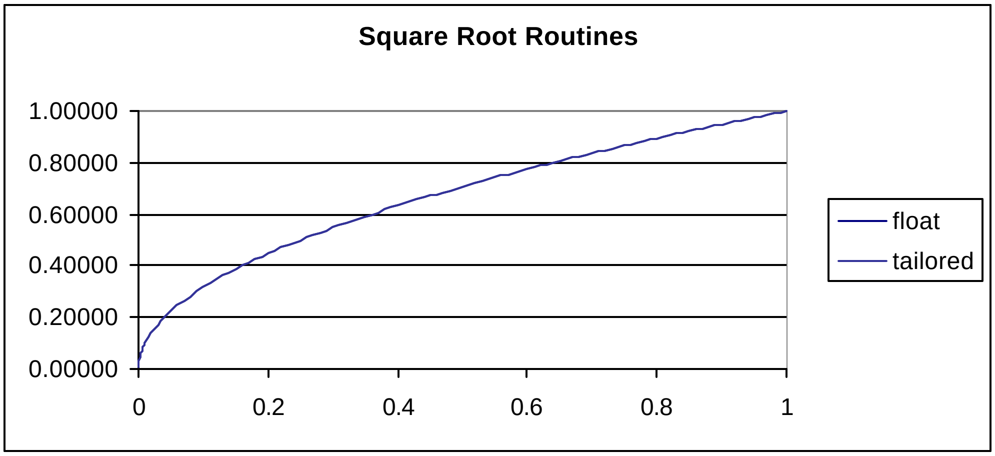

Figure 2.1:Overall Comparison of Square Root Routines

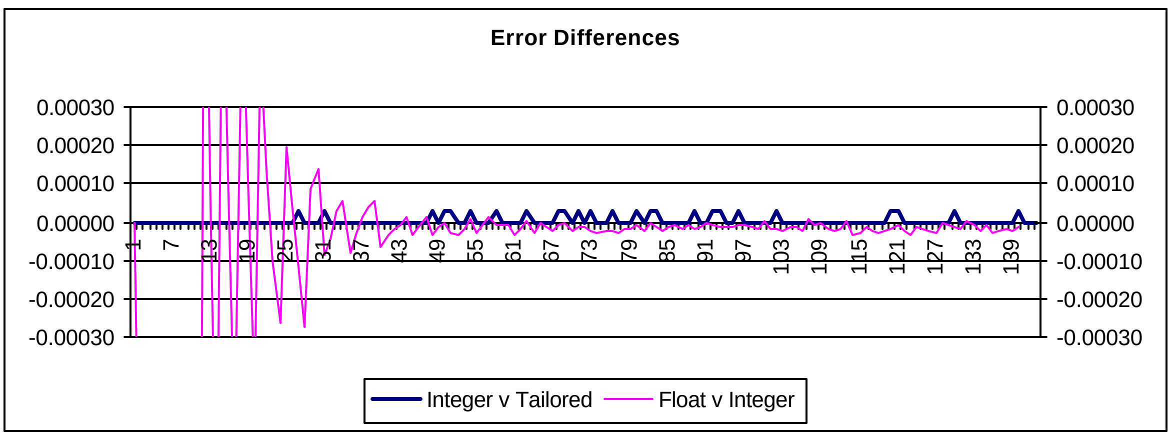

Figure 2.2: Error Comparison of Square Root Routines
(140 test values over the range 0-1)

2.2 Real, Reactive & Apparent Powers

The next concern was to obtain fast and accurate values of the real and reactive powers required for both protection and for the recording of energy consumption (kWh import, kWh export, kVArh import, kVArh export & kVAh). Five algorithmic options were considered:

1. from instantaneous voltage & current (single-phase)
2. from instantaneous voltage & current (three-phase)
3. from fundamental components of voltage and current (single-phase)
4. from fundamental components of voltage and current (three-phase)
5. using three-phase voltage and current space-vectors [3]

Analysis showed:

- although options 1 and 2 provided good estimates of the real (active) power, they were not satisfactory with regard to the estimation of reactive powers.
- options 1 and 3 were not accurate when unbalance was present
- options 4 and 5 both provided accurate estimates of the real and reactive power in the presence of credible levels of unbalance and waveform distortion. In particular:
    - negative sequence at fundamental frequency
    - third harmonics (zero sequence)
    - fifth harmonic (negative sequence)
    - seventh harmonic (positive sequence)

  Option 5 required significantly less computational effort than option 4.

Thus option 5 (space-vectors in fixed-point scaled fraction arithmetic) was selected.

2.3 Negative Sequence Current

The last variable whose calculation requires special consideration is the negative sequence current. Algorithmic options considered included:

1. from the fundamental components of the three phase currents (magnitude and phase)
2. using space-vectors
3. using an exact formulae based on the r.m.s. currents of the three phases and assuming no zero sequence component
4. using an approximate formulae based on the r.m.s. currents of the phases and assuming no zero sequence component

In view of the star-delta connections of typical generator step-up transformers, current measurements on the LV side of transformers would be shielded from zero sequence current originating from the power system. However, option 3 involves the squaring and square rooting of small quantities, which in view of the fixed point arithmetic could result in significant quantization error. As options 1 and 2 were computational heavy, it was decided to use a very simple formula based on the differences of r.m.s. magnitudes between the phases, which is accurate to within 10% of the actual negative sequence level.

3 Low Cost Algorithm Development Environment

Excel with Visual Basic for Applications (VBA) was explored as a potential low cost algorithm development environment for both an electronic protection module and an electronic governor module.

3.1 Protection Module Development

For the development of the protection module, a test waveform facility in Excel / VBA was established. This calculates three-phase voltage and current waveforms allowing for:

- frequency variation
- power factor variation (i.e. current phase angle relative to voltage phase angle)
- negative sequence voltage and current
- three-phase harmonics with appropriate phase sequence orientations, i.e.

Harmonic	Sequence Orientation
3rd harmonic	zero
5th harmonic	negative
7th harmonic	positive

Floating-point algorithms for the calculation of the following power system parameters were then derived and tested using the waveform test facility (see Figure 3.1):

- r.m.s. voltage and current
- real, reactive and apparent powers
- third harmonic voltage
- negative sequence current

Time	Voa	Ioa	Vob	Iob	Voc	Ioc	Inputs	Voltage	Current	Outputs	Exact	Floating	Fixed
0.0000	0.0000	1.3181	-1.2247	-1.1028	1.2247	-0.2153	Freq	60.000	n/a	V1rms	1.00125	1.00125	0.99998
0.0010	0.6065	1.4139	-1.3368	-0.6801	0.9262	-0.7338	Fund Amp	1	1	V2rms	1.00125	1.00125	1.00082
0.0021	1.0500	1.2944	-1.3160	-0.1538	0.4160	-1.1406	Fund phase	0	1.2000	V3rms	1.00125	1.00125	1.00082
0.0031	1.2795	0.9779	-1.1490	0.3959	-0.2117	-1.3737	3rd harm A	0.050	0.000	Iarms	1.00000	1.00000	0.99907
0.0042	1.3435	0.5125	-0.7778	0.8853	-0.7778	-1.3977	3rd harm P	0.000	0.000	Ibrms	1.00000	1.00000	0.99968
0.0052	1.2795	-0.0310	-0.2117	1.2399	-1.1490	-1.2090	5th harm A	0.000	0.000	Icrms	1.00000	1.00000	0.99976
0.0063	1.0500	-0.5697	0.4160	1.4058	-1.3160	-0.8361	5th harm P	0.000	0.000	V3n	0.05000	0.05000	0.04997
0.0073	0.6065	-1.0217	0.9262	1.3577	-1.3368	-0.3360	neg seq A		0.0000	P	1.08707	1.08707	1.08261
0.0083	0.0000	-1.3181	1.2247	1.1028	-1.2247	0.2153	neg seq P		0.0000	Q	-2.79612	-2.65631	-2.65522
0.0094	-0.6065	-1.4139	1.3368	0.6801	-0.9262	0.7338	Vdel2	FALSE		S	3.00000	2.87014	2.86732
0.0104	-1.0500	-1.2944	1.3160	0.1538	-0.4160	1.1406	transf	FALSE		pf	-0.36236	-0.37875	-0.37756
0.0115	-1.2795	-0.9779	1.1490	-0.3959	0.2117	1.3737				I2	0.00000	0.00000	0.00000
0.0125	-1.3435	-0.5125	0.7778	-0.8853	0.7778	1.3977				freq	60.00000	60.00000	60.00000
0.0135	-1.2795	0.0310	0.2117	-1.2399	1.1490	1.2090							
0.0146	-1.0500												
0.0156	-0.6065												
0.0167	0.0000												

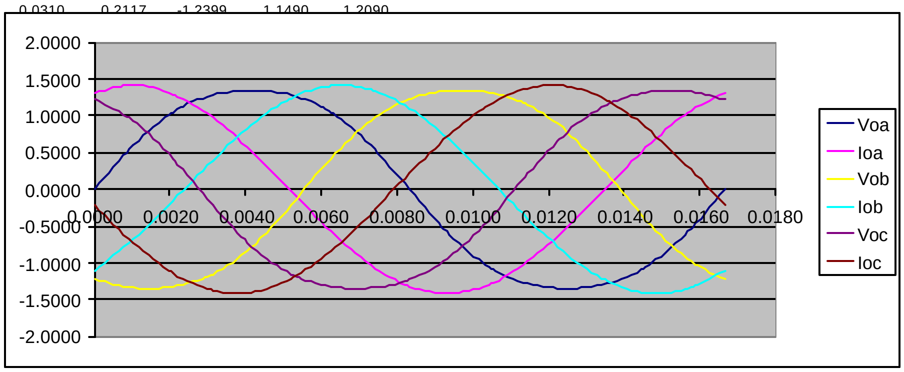

Figure 3.1: Excel / VBA Protection Algorithm Test Facility

Algorithms were then written in 16-bit fixed-point scaled fraction arithmetic, and their results matched to the floating-point versions. This included the modeling of ADCs, with allowance for scale and offset error.

Movement of the algorithms from the Excel / VBA environment to the target microcomputer C environment was found to be very straightforward, generally involving little more than reformatting of commands. An overview of the relationship between the two environments is shown in Figure 3.2.

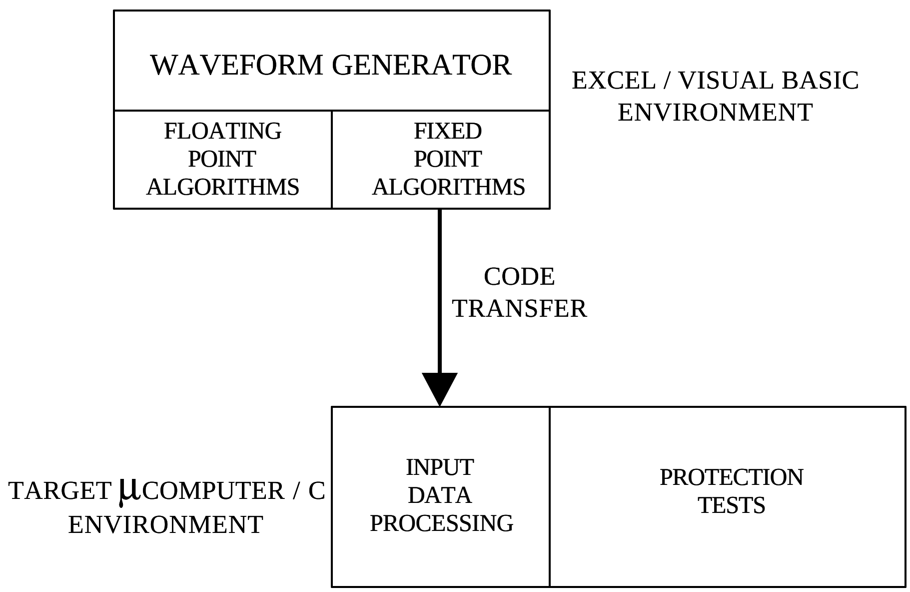

Figure 3.2: Protection Algorithms Development Environment

3.2 Governor Module Development

For the development of the governor control laws, and in accordance with the appropriate IEEE standard [4], the starting point was to establish a simulation facility. Using the Excel / VBA environment, a model of a single hydro machine to an infinite bus was initially established, and used to design speed, power and gate control loops. Resulting time-responses were plotted using Excel's graphical facilities (see Figure 3.3).

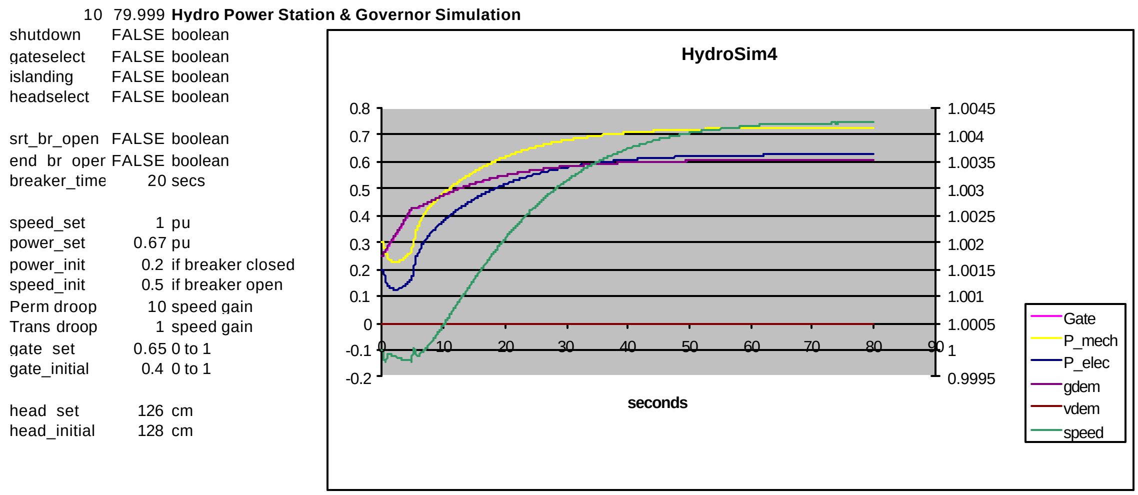

Figure 3.3: Excel / VBA Governor Algorithms Test Facility

This enabled the governor control laws to be developed as floating point algorithms within the Excel / VBA environment. As the governor specification matured, additional control modes such as head control and islanding operation were added. In line with this development, the hydro machine model was appropriately extended, see Figure 3.4.

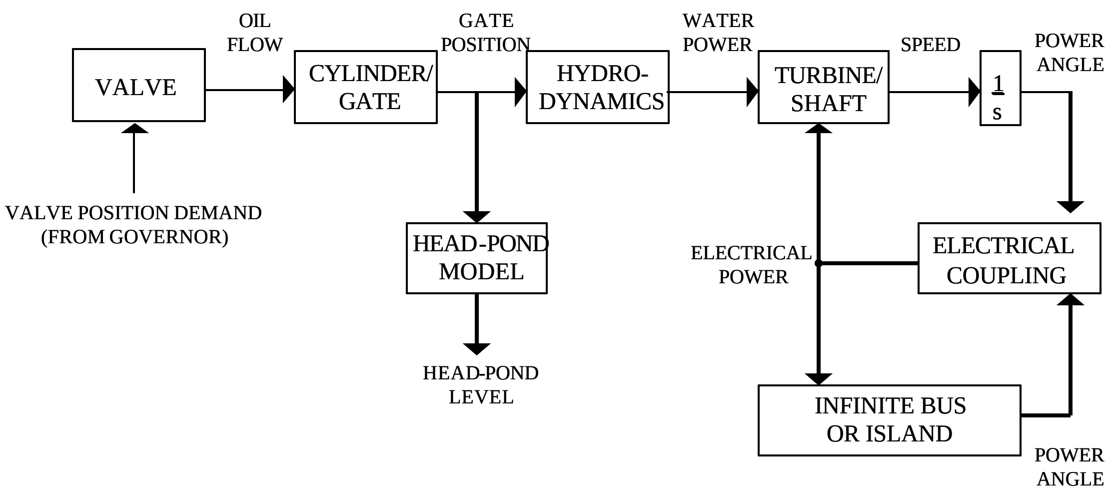

Figure 3.4: HydroSim Model

The control laws were then copied across into the C-language environment of the target microprocessor, with command re-formatting as appropriate. Timing analyses showed that floating point arithmetic was adequately fast for the bulk of the computation in the target microcomputer.

In order to verify the specifications for analog-to-digital converters and digital-to-analog converters, certain parts of the control laws, in the Excel / VBA environment, were re-coded in fixed-point arithmetic and subsequently transferred to the target C-environment.

In addition, the hydro-plant model was also transferred to the target C-environment, as this provided a versatile closed-loop test facility for the target software.

Excel / VBA was further utilized for the plotting and analyzing of time-responses obtained from closed-loop software testing. Using a serial data connection from the target microcomputer to a PC equipped with a HyperTerminal facility, time-series data were downloaded. Then a Visual Basic macro was written to graphically display and analyze the time-series data. Two additional advantages of this approach are:

- it enables recursive file-based testing of the software in the target environment
- it provides a facility for commissioning, field testing, and User diagnostics

An overview of the relationship between the two environments is shown in Figure 3.5.

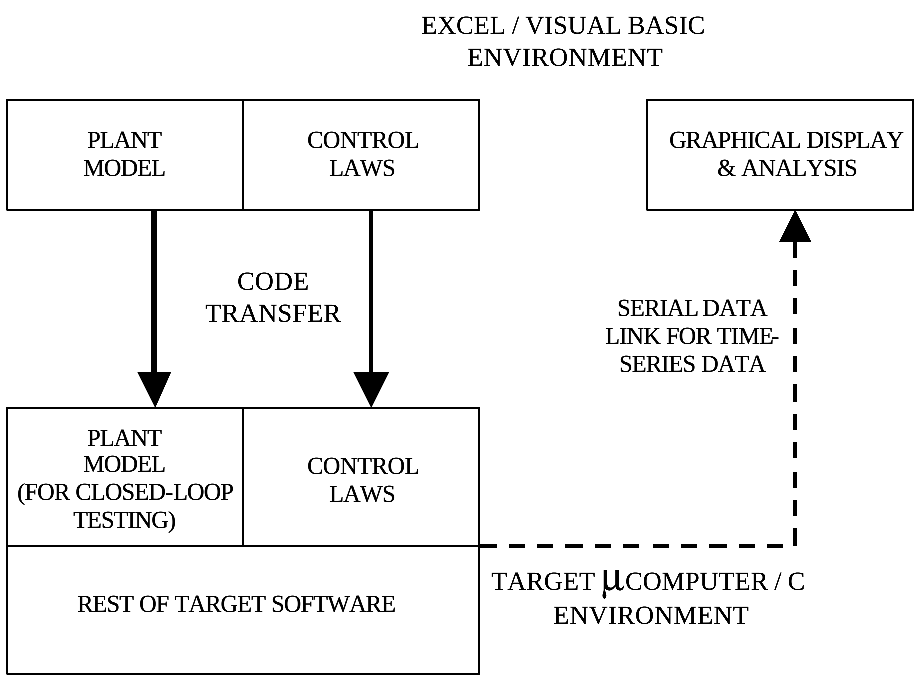

Figure 3.5: Governor Algorithms Development Environment

4 Conclusions

The increased speed provided by tailored algorithms has enabled the capability for multifunctional protection using a low-cost state-of-the-art microcomputer facility. The algorithms covered a range of features:

- fixed-point scaled fraction arithmetic
- fast square-rooting with fixed-point scaled fraction arithmetic for r.m.s. calculation
- space-vectors with fixed-point scaled fraction arithmetic for power calculation
- simplified algorithm for negative sequence current calculation

Excel with Visual Basic for Applications on an everyday PC was found to be an effective low-cost versatile environment for the development and testing of small hydro electronic protection and control algorithms. In particular, this environment was found effective for:

- the development of tailored algorithms for protection
- the development of a waveform simulation capability for testing of the tailored protection algorithms
- tailored simulations for testing and development of governor control laws
- graphical display and analysis of closed-loop time-series data.
- comparison of floating-point and fixed-point implementations of algorithms
- initial implementation of the algorithms in the target microcomputer software environment
- recursive file-based testing of software

The simulation tools provide a low cost alternate environment accessible to many small companies and educational institutions looking to provide as close to real life testing as possible, and a reduction in the requirements for both expensive voltage and frequency hardware simulators and turbine test facilities.

The techniques developed and utilized show that not only can the latest generation of low cost microcomputers be employed for control and protection functions, but also that the derived solutions are further evidence that an integrated platform approach offers many benefits for addressing the needs of this particular segment of the hydro industry.

Companies have now started to integrate the result of this research into their designs and have shown that the tools and algorithms developed are providing the anticipated benefits. Low cost embedded control systems combined with integrated software configuration tools are now gaining acceptance around the globe and offer a viable alternative to the more generic control and protection approach.

5 References

[1] Y Grandmaitre, "Low Cost, Operate Friendly Controls for Small Hydro – Fact or Fiction?", Presented at HydroVision 2000, North Carolina, August 2000.

[2] IEEE Std C37.102-1995, IEEE Guide for AC Generator Protection.

[3] I A Erinmez & A M Foss (Editors), *Static Synchronous Compensator (STATCOM)*, Working Group 14.19, CIGRE Technical Brochure 1998.

[4] ANSI/IEEE Std 125-1988, IEEE Recommended Practice for Preparation of Equipment Specifications for Speed-Governing of Hydraulic Turbines Intended to Drive Electric Generators.

Authors

Aidan Foss PhD, CEng, graduated in mathematics from Cambridge University and completed his PhD on turbine control with Imperial College. From 1976 to 1990, he specialized in computer control and simulation, and was Vice-Chairman of the United Kingdom Simulation Council. In 1990, he joined the National Grid Company, focusing on power applications, including auditing and modeling of generator control systems. In 2001, he moved to Ottawa where he is a consultant covering power, control and simulation.

Yves Grandmaitre, CSP, has been active in selling and interfacing with industrial controls for over fifteen years. His experiences have spanned the pulp and paper industry, petrochemical, waste water and many more. Mr. Grandmaitre practices a hands-on approach to selling and has been involved in many installations and commissioning of control systems. He has also traveled extensively and written articles promoting the benefits of an embedded application specific controller approach for small hydro sites.

John Morton, B.Eng., Carleton University, Electrical Engineering. Mr. Morton specializes in high performance micro-controller development focusing on optimizing complex mathematical algorithms in assembler-based languages. He is also responsible for hardware development and integration of the latest Powerbase governor and generator protection systems, both of which utilize high performance micro-processing designs. Mr. Morton has extensive field and application experience involving small hydraulic turbines and synchronous generator protection implementation.

William Kemp, V.P. of Engineering, has over 20 years experience in the development of high performance embedded control systems, focusing on scalable hardware and software solutions to the on and off grid power generation industry. Also experienced in PV and wind technology, Mr. Kemp is the principal system architect of the Powerbase Platform. He has traveled extensively promoting to industry the effectiveness of the Powerbase platform as an ideal solution for the small hydro protection and control market.