J. Indian Inst. Sci., July–Aug. 1987, 67, pp. 307–318

IISc. THESES ABSTRACTS

Thesis Abstract (Ph.D.)

Quantization problems in detour-phase digital holograms by V. V. Krishna Reddy.
Research supervisor: P. S. Naidu.
Department: Electrical Communication Engineering.

1. Introduction

Computer-generated holograms have many applications in diverse areas such as storage, processing and display of information, creation of difficult-to-obtain reference wavefronts, as logic-switching elements in optical computing, etc. One particularly important class of holograms is based on the 'detour phase' principle developed by Lohmann and co-workers. These are essentially binary Fourier transform holograms with the most notable ones being the Lohmann Lee and Burckhardt holograms[1] and the double-phase hologram (DPH)[2].

Noise in computer-generated hologram reconstruction can be traced basically to two sources: (i) Representation-related errors due to approximations involved in the particular holographic technique used and (ii) quantization errors introduced while plotting the hologram on a display device. For most detour-phase binary holograms produced using general purpose graphic displays, quantization noise will actually limit the image quality.

Previously, some workers have evolved 'comprehensive' error models[3] for detour-phase holograms in order to quantify their performance. All types of errors were taken care of by a single expression for each hologram. Of necessity, this expression is both lengthy and complicated rendering the use of these models a rather formidable task. Moreover, it cannot be easily determined which hologram has the smallest quantization error.

2. Scope

In this thesis the quantization formats of some detour-phase binary holograms are simulated and studied in detail under the relevant constraints. An in-depth study of Haskell's generalised detour-phase hologram[4] is, however, avoided as its performance is limited only by the inherent representation approximations. For the purpose of evaluation, the quantization errors are estimated in both the Fourier and image planes. Certain techniques that help to reduce quantization noise like phase-coding (spectrum spreading) and prequantization are also applied.

3. *Results and discussion*

To begin with, the question of allotting the quantization levels between the Fourier amplitude and phase in an 'optimum' manner[5] is addressed. It is shown that this allocation based on conditions of bit-rate limited digital transmission of Fourier plane information is not appropriate as far as

digital holography is concerned. An immediate implication is that the rectangular (Lee) quantizer has a significant advantage over the uniform polar (Lohmann) format[6].

The estimated results also indicate that whenever phase-coding is employed, the Lee hologram has the smallest quantization error. Its mean square transform error is smaller than Lohmann or Burckhardt quantizers by about 10% and the DPH format by over 30%[7]. In fact, the error for Lee hologram approaches that associated with the optimum non-uniform polar quantizer derived theoretically[8]. Considering that this hologram also simplifies the task of reducing the so-called 'detour-phase error', it is certainly the best choice in these conditions.

Iterative phase-coding techniques similar to the Gerchberg-Saxton algorithm have been extensively used in recent times[9] to reduce image plane errors. These methods initially use random phase-coding and then iteratively select a suitable object-specific phase-code that gives minimal image error. One such method was applied to the four holograms mentioned earlier. For every hologram the image signal-to-noise ratio showed a 20–30% improvement over the randomly phase-coded case. The Lee hologram still maintained the best image fidelity.

An interesting inversion in performance levels is noticed between the Burckhardt hologram and its variant developed by Chavel and Hugonin[10,11]. The latter yields a better reconstruction when the object is phase-coded while the Burckhardt hologram has a relatively superior performance when phase-coding is not employed. It is further noted that Burckhardt quantizer has a quasi-hexagonal format with a larger number of output levels than the Lohmann quantizer. Yet, its performance for phase-coded objects remains below that of the Lohmann hologram; the reason for this is explained in the thesis.

When phase-coding cannot be employed (as in image processing applications where the image phase has to be preserved), the performance of Lohmann, Lee and Burckhardt holograms is of the same order. Now, reducing the phase representation error is a difficult proposition for the Lohmann hologram when compared with the other two. But, this handicap is more than offset

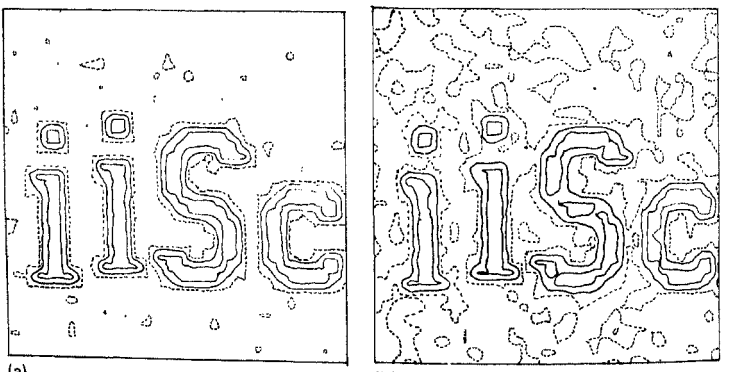

FIG 1. Equi-magnitude contours for simulated reconstructions of test object subjected to quantization (Q = 10 levels) a) Lee quantizer, image SNR = 33.5; b) Prequantized DPH, image SNR = 14.3.

considering that on incremental displays the Lohmann method needs only half the plotting effort involved in generating either a Lee or a Burckhardt hologram.

Irrespective of whether phase-coding is employed or not, the DPH performs quite poorly. The corresponding quantization format provides satisfactory explanation for the large amount of errors. It also points out a hitherto overlooked necessity for 'down-clipping' in the DPH. Further, prequantization has been demonstrated by other workers[12] to reduce quantization error in this hologram. A detailed investigation of this was undertaken[13] and we found that even under the best of conditions, the prequantized DPH remains below par when compared with other detour-phase holograms (fig 1).

This evaluation of different quantizers should be helpful in the selection of a suitable hologram for any given application. One interesting application of digital holography is spatial frequency filtering for code-translation. This thesis describes a new filter for two-way code translation[14] which overcomes a certain difficulty in the output plane found with existing formulations. The obtained results show that this filter works satisfactorily even under the modest quantization levels common to digital holography.

References

1. Lee, W-H. — In *Progress in optics*, E. Wolf (ed), 1978, Vol. 16, pp. 119–232, North-Holland, Amsterdam.
2. Hsueh, C.K. and Sawchuk, A.A — *Appl. Opt.*, 1978, **17**, 3874.
3. Bucklew, J. and Gallagher, N.C. Jr. — *Appl. Opt.*, 1979, **18**, 2861
4. Haskell, R.E. — *J. Opt. Soc. Am.*, 1973, **63**, 504A.
5. Gallagher, N.C. Jr. — *Appl. Opt.*, 1978, **17**, 109.
6. Krishna, V.V. and Naidu, P.S. — *Opt. Acta*, 1984, **31**, 795.
7. Krishna, V.V. and Naidu, P.S. — *Opt. Acta*, 1985, **32**, 1373.
8. Pearlman, W.A. and Senge, G.H. — *IEEE Trans. Commun.*, 1979, **COM-27**, 101.
9. Fienup, J.R. — *Opt. Engng*, 1980, **19**, 297.
10. Chavel, P. and Hugonin, J.P. — *J. Opt. Soc. Am.*, 1976, **66**, 989.
11. Bartelt, H.O. and Forster, K-D. — *Opt. Commun.*, 1978, **26**, 12.
12. Rines, K.D. and Gallagher, N.C. Jr. — *Appl. Opt.*, 1981, **20**, 2008.
13. Krishna, V.V. and Naidu, P.S. — submitted to *Opt. Commun.*, 1986.
14. Naidu, P.S. and Krishna, V.V. — *Proc. IEEE Int. Conf. Computers, Systems Signal Processing*, Bangalore, India, 1984, pp. 1658–1660.

Thesis Abstract (Ph.D.)

Some aspects of synchronous machine modelling and interfacing techniques for simulation of transient phenomena by R. Ramanujam.
Research supervisors: H.P. Khincha, K. Parthasarathy and V.A. Sastry.
Department: Electrical Engineering.

1. Introduction

Modern power systems are subjected to a variety of transients due to intended or inadvertent switching operations. In terms of time constants and observation intervals they span a wide range, from micro seconds to minutes. From this spectrum two types of transients which are of interest to power system planners and analysts are chosen for investigation. They are: (i) electromagnetic transients and (ii) electromechanical transients. Traditional interest of the analysts was confined to the second type. The analysis of this type of transient was limited to evaluation of the ability of rotating machines to remain in synchronism in the event of a disturbance inception and subsequent removal. This is commonly referred to as transient stability problem. Digital computer programs which replaced the earlier analog methods are used for transient stability[1]. They are, however, limited in their scope to analyse dynamics of exchange of energy between machines and network at power frequency only. Due to simplifying assumptions made, transient stability programs (TSP) cannot be used to analyse transients which involve energy interchange between machines and network at frequencies significantly different from power frequency. These transients are analysed using electromagnetic transients program (EMTP) to which detailed multi-mass synchronous machine models are interfaced[2,3].

2. Investigations and discussion

The thesis deals with modelling of synchronous machines (SM), interfacing techniques and numerical solution aspects associated with both types of transients. Two common problems associated with them are synchronous machine modelling including determination of simulation parameters and numerical integration methods used to solve the associated differential equations. A general equivalent circuit for SM is developed here starting from Park's equations by appropriate rescaling of rotor variables. It has been shown that SM model implemented currently in EMTP and the one used here, Olive's model[4], can be derived as special cases of the general model. A condition for successful conversion of manufacturer-supplied data to simulation parameters by an existing procedure is derived. A method of data conversion if the condition is violated is also described. Additional independent methods of data conversion are presented. An SM interfacing scheme for UBC EMTP based on stator flux prediction as opposed to earlier method of stator current prediction has been described. Results are presented to validate the SM interface to EMTP. The approach followed in the interfacing scheme has been proven to result in a numerically stable simulation—even for uncommon values of stepsize. A different method of handling saliency has been built into that interface. A very general method of computing harmonics existing in machine and network during unbalanced steady state has been described. An earlier proposed method of computing harmonics in SM terminated in a lumped load[5] is treated as a special case. The harmonics computed by the method proposed makes comprehensive initialization of SM and network possible, thereby yielding 'hash-free' simulation results. Elementary ideas of theory of linear vector spaces have been used to derive a necessary condition for maintaining power

invariance between phase and Park's coordinates while going through symmetrical component coordinates. Computation of double frequency rotor currents by an earlier proposed method[6] turns out to be a special case of the method proposed here. An EMTP interface which performs automatic computation of network initial conditions and which generates data for subsequent transient simulation has been described. The interface has been implemented for the UBC EMTP. In the area of slower electromechanical transients, a method of modelling damper windings in a simultaneous implicit type algorithm has been presented. Results from this method are presented and corroborated from two independent sources. The results obtained by making the algorithm non-iterative as far as saliency is concerned were found to have excellent agreement with the original algorithm. A practical application of some of the concepts for TSP transients involving real-time simulation of electrical system of 1300 MW nuclear power plant training simulator has been described.

Properties of trapezoidal rule which is used for simulation of electromagnetic and electromechanical transients are analysed. Two groups of sources of non-physical time-step oscillations reported to have occurred in EMTP simulations were identified. The inherent cause of those oscillations was uncovered. Equivalence between two basic approaches proposed earlier[7,8] to overcome this problem of numerical oscillations has been established. Mathematical basis for explaining the periodical physical reversion of element behaviour (inductance to capacitance and *vice versa*) has been laid down. Trapezoidal rule is compared and contrasted with two serious contenders for simulation of power system dynamics, namely, Backward Euler and Gear's second order methods. A modified form of trapezoidal rule to make simulation results to alleviate the numerical noise problem has been proposed.

References

1. DOMMEL, H.W. AND SATO, N. — Fast transient stability solutions, *IEEE Trans.*, 1972, **PAS-91**, 1643–1650.
2. DOMMEL, H.W. AND DOMMEL, I.I. — *Transients program user's manual*, The University of British Columbia, Vancouver, Canada, Aug. 1978.
3. BRANDWAJN, V. AND DOMMEL, H.W. — Interfacing generator models with an electromagnetic transients program, Paper No. A76 359-0, presented at *IEEE PES Summer Meeting*, Portland, July 1976.
4. OLIVE, D.W. — Modelling of synchronous machines for digital studies, Course Text, *IEEE tutorial course on digital simulation of electrical transient phenomena*, 1980.
5. ROARK, J.D. AND GROSS, C.A — Unbalanced synchronous machine analysis using frequency domain methods, presented at *IEEE PES Summer Meeting*, Los Angeles, California, July 16–21, 1978.
6. BRANDWAJN, V., SCOTT MEYER, W. AND DOMMEL, H.W. — Synchronous machine initialization for unbalanced network conditions within an electromagnetic transients program, presented at *IEEE PES Summer Meeting*, 1978.
7. BRANDWAJN, V. — Damping of numerical noise in EMTP solution, *EMTP Newslett.*, 1982, **2**, 3–6.
8. ALVARADO, F.L., LASSETLER, R.H. AND SANCHEZ, J.J. — Testing of trapezoidal integration with damping for the solution of power system transient problems, *IEEE Trans.*, 1983, **PAS-102**, 3783–3790.

Thesis Abstract (Ph.D.)

Parallel algorithms for compilation by Y. N. Srikant.
Research supervisor: Priti Shankar.
Department: Computer Science and Automation.

1. Introduction

The design of parallel algorithms for the compilation process is considered in this thesis. Our algorithms use an SIMD (Single Instruction Stream Multiple Datastream) computer with shared memory[1]. We also assume that read and write conflicts are not permitted.

Rather surprisingly, the problem of designing compilers to run on parallel computers has received very little attention[2–5]. Specifically compilation algorithms which run on SIMD machines are even rarer[3,4]. In this thesis, we present several new efficient parallel algorithms for the compilation process on SIMD computers and the main contributions may be summarised as below:

(i) design of parallel algorithms for syntax tree construction from arithmetic expressions,

(ii) design of parallel algorithms to restructure arithmetic expressions to make them more suitable for parallel evaluation,

(iii) design of parallel algorithms to generate code for SIMD computers from syntax trees of arithmetic expressions,

(iv) design of parallel algorithm for parsing PF(k) – parsable languages – a subclass of regular languages,

(v) design of a new model of specification of the syntax of programming languages and a parallel parsing algorithm for the same.

2. Brief details of the algorithms

We consider the tasks of checking the wellformedness, construction of the abstract syntax tree, and code generation from arithmetic infix expressions using SIMD computers. Further we present efficient parallel algorithms for restructuring arithmetic expressions to make them more suitable for parallel evaluation. Only sequential algorithms for this task have been reported before. All our parallel algorithms have the important feature that they can deal with multiple expressions simultaneously. All the algorithms except the code-generation algorithm run in $O(\log^2 n)$ time on n processors where n is the sum of the lengths of the expressions. The parallel code-generation algorithms generate code (called vector quadruples) for an SIMD machine and requires $O(n)$ time, on n processors where n is as before.

Next, we consider parallel parsing algorithms for regular languages. We define a class of languages called PF(k)-parsable languages which are a subset of regular languages and present efficient parallel parsing algorithms (requiring $O(\log n)$ time on n processors) for the same. We provide necessary and sufficient conditions for a regular language to be PF(k)-parsable and show that PF(k)-parsability is a decidable property for regular languages.

Lastly we propose a parallel parsing strategy known as Sort-PF(k)-parsing for programming languages. We consider programming languages with endmarkers for each construct in the language (var-endvar, procedure-endproc, begin-end, if-then-else-endif, while-do-endwhile, etc.).

We show how the specification of the syntax of such a programming language in terms of PF(k)-parsable languages and semi-dyck sets (called Hierarchical Language Specifications (HLS)), leads to an efficient parallel parsing algorithm (taking $O(\log^2 n)$ time on n processors). We also show how the abstract syntax tree representation of a program may be constructed in a parallel manner.

References

1. Wyllie, J.C. — *The complexity of parallel computations*, Ph.D. Thesis, Cornell University, 1979.
2. Baer, J.L. and Bovet, D.P. — Compilation of arithmetic expressions for parallel computations, *Proc. IFIP Cong.*, North-Holland Publishing Company, Amsterdam, 1968, pp. 340–346.
3. Bar-On, I. and Vishkin, U. — Optimal parallel generation of a computation tree form, *ACM Trans. Programming Languages Systems*, 1985, 7, 348–357.
4. Fischer, C.N. — On parsing and compiling arithmetic expressions on vector computers, *ACM Trans. Programming Languages Systems*, 1980, 2, 203–224.
5. Schell, R.M. Jr. — *Methods for constructing parallel compilers for use in a multiprocessor environment*, Ph.D. Thesis, Computer Science Dept., Univ. of Illinois, Urbana, Ill., 1979.

Thesis Abstract (Ph.D.)

Sea-surface spectrum from aerial photographs: Model studies using microprocessor-controlled optical scanning by Y. Venkatarami Reddy.
Research supervisor: P. S. Naidu.
Department: Electrical Communication Engineering.

1. Introduction

The sea-surface spectrum is of great interest in studies such as radar scattering[1], wave and weather forecasting[2], coastal engineering[3], etc. Stilwell[4] first proposed a method of obtaining sea-surface spectrum from aerial photographs. Many other workers have since contributed to the development of this method, which is based on the principle that the camera illumination (I) is linearly related to the local surface normal (φ) angle

$$I = I_0 + I' \varphi \cos \psi$$

where $I' = K [2L' (\theta) \Gamma (\beta) + L(\theta) \Gamma' (\beta)] =$ a constant and ψ azimuthal angle of illumination, $L(\theta)$ and $\Gamma(\beta)$ are the illumination function and reflectivity of sea water surface respectively.

The present study is aimed at physical modelling of the sea surface and relating its photograph taken under different illumination conditions to the spectrum of the surface. The purpose is to verify the theoretical principles presented by Stilwell.

2. Experimental programme

The model studies is essentially divided into two parts. The first part is the development of instrumentation to measure the optical Fourier transform. The second part is the modelling of sea

surface by means of a plastic-coated paper whose surface reflectivity characteristic is quite similar to that of the water surface.

A microprocessor-controlled photodiode array was developed to measure the optical Fourier transform[5]. This system is developed around a microprocessor (8085) development board (MDB). It consists of a linear 512 photodiode array, a stepper motor, 18-column numeric printer and a floppy disc interfaced to the MDB. The array is mounted vertically on a horizontal translator driven by a stepper motor. The data is read into the memory of MDB under programme control and is then transferred to floppy disc. If necessary a print-out can also be obtained. The data can also be sent over telephone lines to DEC 1090 main frame computer for further processing, if necessary. The system is capable of scanning optical intensities in any plane and measuring the light intensity at rectangular sampling intervals. The array is placed vertically at one edge of the plane to be scanned and the output from 512 diodes will provide the light intensity at 512 points spaced at 25.4 microns apart. The array is moved in steps to cover the complete plane. The data is in a matrix form with 512 rows corresponding to 512 diodes and columns equal to number of steps required to cover the sample area. The system specifications are given in Table I.

Three types of paper models, namely, (1) one-dimensional sinusoidal wave surface (2) saw tooth wave surface (3) high frequency sinusoid modulating low frequency sinusoid have been developed. The models were illuminated both by diffused light source and by clear sky light. The angle of illumination and the camera angle were varied to ascertain the optimum illumination conditions and the camera orientation. The wave height is also varied to study the range of linear mapping. As the exposure time is short it may be assumed that the sea surface remains 'frozen' during this period. The photographs were processed on an optical processor. A lens is used to obtain the Fourier transform of the photograph negative and is measured with the micro-processor-controlled photodiode array. The absolute spectral magnitude, as it depends upon the film processing, is of little use. Only the relative magnitude is useful provided the photographs are taken and processed under identical conditions.

Table 1
System specifications

Y-direction sampling	:	25·4 micrometers
X-direction sampling	:	variable with a minimum of 25 micrometers
Operating frequency	:	25 KHz
Time required to acquire the data into MDB memory	:	0·02 s
Time to print out the 512 diode output	:	173 s
Time to store the 512 diode output on floppy disc	:	1 s
Saturation voltage	:	8V
Dark level voltage	:	0V
Operating temperature	:	30°C
Signal-to-noise ratio	:	230
Maximum size of pattern that can be scanned	:	1·3 × 10 cm

3. Results and conclusions

The spectrum of the photograph of a sinusoidal surface illuminated either by a diffused light source or clear sky light is found to be proportional to the spectrum of sinusoidal surface. This linear relationship fails whenever the wave height is greater than one third of the wave length. For a surface that can be expressed as a sum of two or more Fourier components (Model II) and when photographed appropriately, its spectrum can be obtained from the photograph provided all Fourier components satisfy the above constraint on the amplitude. This was demonstrated for a ramp model. For a complex surface where two sinusoidal wave surfaces are interacting non-linearly (Mode-III), the spectrum of the photograph can identify the interacting sinusoidals, both their frequencies and amplitudes.

The angle of illumination is an important factor. At lower angles the shadowing would cause generation of harmonics and at higher angles the spectrum shows no evidence of surface waves. The useful range of illumination angle is 40–60°. This is true for both diffused light and clear sky light.

Finally, the camera angle should be above 40°. At lower camera angles higher order harmonics are generated.

References

1. Chia, R.C. — *The theory of radar backscatter from the sea*, Ph.D. dissertation, University of Kansas, Lawrence, 1968.
2. Munk, W.H., Miller, G.R., Snodgrass, F.E. and Barber, N.F. — Directional recording of swell from distant storms, *Phil. Trans. Roy. Soc. Lond., A.*, 1962, **255**, 505–584.
3. Panickar, N.N. and Borgman, L.E. — *Directional spectra from wave of gause array*, Hydraulic Engineering Lab., College of Engineering, Univ. of California, Berkeley, HEL. 1–16, 1970.
4. Stilwell, D. Jr. — Directional energy spectra of the sea from photographs, *J. Geophys. Res.*, 1969, **74**, 1974–1986.
5. Reddy, Y.V., Kalpagam, K. and Naidu, P.S. — Microprocessor-controlled photodiode array for measurement of diffraction patterns, *Microprocessors Microsystems*, 1985, **9**, 226–230.

Thesis Abstract (M.Sc. (Engng))

Coordination and performance evaluation of protection schemes — A formal approach by S. Shivakumar.

Research supervisors: H. P. Khincha and Lawrence Jenkins.
Department: Electrical Engineering.

1. Introduction

An electric power system should operate in a manner that ensures the availability of electrical energy, with minimal interruption, to every consumer connected to the system. Fluctuations in

the operating conditions of the power system renders this task difficult. Protection systems are designed to guard the power system against abnormal operating conditions. In order to ensure reliability in this critical task, utilities generally provide fast primary protection along with slower backup protection. However, to ensure that a minimum portion of the system is disrupted, the operations of such primary backup pairs of relays have to be coordinated.

In an attempt to systematize the coordination of relays in multiloop networks, Dwarakanath and Nowitz[1] proposed a graph theoretic approach. This effort established the importance of topological analysis in relay coordination. Topological analysis of a network involves the identification of all possible primary backup pairs of relays in the network. The major drawback of this work was its inability to analyse networks with multiterminal lines.

Damborg and Venkata[2] extended this work to include multiterminal lines. The other significant contributions made were:

(1) a formal specification of the coordination criteria,

(2) proof for the rapid convergence of the coordination algorithms.

Further extensions by Ramaswami *et al*[3] resulted in better algorithms for topological analysis. One of the major computational efforts during topological analysis is in identifying the Break Point Set (BPS). In the literature, a BPS is defined to be a minimal set of relays starting from which all the other relays in the network can be coordinated. In 1986, Bapeswara Rao and Sankara Rao[4] showed that the graph theoretic approaches[1-3] do not always find the smallest BPS, and proposed an extension to the scheme so that the smallest BPS may be found.

2. Investigations and discussion

In this thesis, an alternative model for the network topology has been developed based on the notion of functional dependencies arising in relational database theory[5].

The thesis establishes that it is useful to distinguish between two types of BPSs — minimal and minimum. A minimal BPS is a BPS such that no proper subset of it can be a BPS. A minimum BPS is the smallest BPS for the network.

It has been shown that the problem of finding a minimum BPS is NP-complete[6]. Thus, there probably does not exist a polynomial time algorithm to find a minimum BPS[6]. The graph theoretic approaches[1-3] use minimal BPSs[4], thus establishing utility of minimal BPSs. However, the computational time required[1-3] to identify a minimal BPS grows exponentially as the size of the network grows.

Functional dependencies (FD) have been used to capture all the constraint relationships in network topologies. The problem of finding a minimal BPS has been shown to be identical to that of left reducing a given FD. Standard algorithms in the literature[5,7] have been adapted to develop a fast algorithm for topological analysis.

This scheme results in polynomial time algorithms in contrast to the existing graph theoretic schemes which have exponential time complexity. The storage requirements for these algorithms are minimal and are hence ideally suited for topological analysis of large systems. In addition, the FD approach is more flexible for use in CAD environments for protection systems engineering.

The FD approach was useful in establishing the inherent intractability of finding a minimum BPS, as opposed to finding a minimal BPS which can be identified in polynomial time, again using

the FD approach. This should be contrasted with the graph theoretic schemes which offer exponential time algorithms for finding minimal as well as minimum BPSs.

Since the task of relay coordination is computationally expensive, it would be very useful to comment on the performance of the existing protection systems. As an initial effort towards modelling and performance evaluation of protection systems, Petri Net models have been developed.

This thesis also presents an initial effort towards modelling and evaluating the performance of protection systems based on Petri Nets[8]. PN, Time PN, Timed PN and Stochastic PN models for protection systems have been developed. Based on these models, some qualitative and quantitative performance measures have been proposed for protection systems.

The qualitative measures *viz.*, conservativeness, boundedness and properness, are global performance measures and reflect, subjectively, the behaviour of the protection system as a whole. The quantitative measures, *viz.*, recoverability and cycle times, essentially reflect the local dynamic behaviour of protection systems. Based on these, global measures, *viz.*, mean recoverability and mean cycle times have been proposed.

The quantitative performance measures are based on associating time delays with various transitions. The major objective of this effort has been to establish the feasibility of adapting Petri Net-based techniques for the evaluation of the performance of protection systems.

In practice, it is known that the time values associated with the transitions are functions of the system operating conditions. Dynamic power system models have been used in the literature to study various aspects of the existing as well as proposed power system networks. If the time values associated with the various transitions are derived based on the output generated from such dynamic power system models, the techniques presented can be used to carry out more meaningful performance studies.

PNs are also very useful in addressing several other related problems in protection systems engineering. Two important applications in rule-based systems for protection engineering and simulation are briefly discussed.

References

1. Dwarakanath, M.H. and Nowitz, L. — An application of linear graph theory for coordination of directional over-current relays, *Electrical power problems: The mathematical challenge*, SIAM, 1980, pp. 104–114.
2. Damborg, M.J. and Venkata, S.S. — Specification of computer-aided design of transmission protection systems, *Final report EL-3337, RP1764-6*, EPRI., Jan. 1984.
3. Ramaswami, R., Damborg, S.S., Venkata, S.S., Jampala, A.K. and Postforoosh, J.M. — Enhanced algorithms for transmission protective relay coordination, *IEEE Trans.*, 1986, PWRD-1, 280–287.
4. Bapeswara Rao, V.V. and Sankara Rao, K. — Computer aided coordination of directional relays: Determination of break points, *IEEE PES Winter Meeting*, Feb. 1987.
5. Maier, D. — *The theory of relational databases*, Computer Science Press, 1983.

6. GAREY, M.R. AND JOHNSON, D.S. *Computers and intractability: A guide to the theory of NP-completeness*, Freeman, San Francisco, 1978.

7. LUCCHESI, C.L. AND OSBORN, S.L. Candidate keys for relations, *J. Computer System Sci.*, 1978, **17**, 270–279.

8. PETERSON, J.L. Petri Nets, *ACM Computing Surv.*, 1977, **9**, 223–252.