A Novel Approach to the Automatic Analysis of Disturbance Data: Technology and Implementation

R. ŽIVANOVIĆ, A. UKIL, J. JORDAAN
Tshwane University of Technology
Nelson Mandela Drive, Pretoria, 0001
SOUTH AFRICA
http://www.tut.ac.za

Abstract: - The analysis of faults and disturbances is a fundamental foundation for a secure and reliable electrical power supply. Huge amount of disturbance data from the digital fault recorders also brings the challenge of automatically converting data to knowledge, which frees the complex and time-consuming manual analysis. This paper presents a novel approach to the automatic analysis of disturbance data. First, the disturbance signal is segmented based on abrupt change detection in the signal model parameter. This is followed by feature vector construction for specific segments and pattern matching using those feature vectors. Recorded disturbance signals from the power network in South Africa have been used for practical testing.

Key-Words: - Automatic disturbance analysis, Abrupt change detection, Semi-parametric approach, Support vector machines.

1 Introduction

The analysis of faults and disturbances was in the past, and will also be in the future, a fundamental foundation for a secure and reliable electrical power supply. The introduction of the digital recording technology opened new dimension in quantity and quality to the fault and disturbance data acquisition, resulting in a huge amount of new information to be available to the power systems engineers. Information from the analysis of digital records can provide much needed insight into the behavior of the power system as well as the performance of protection equipment. Manual analysis of these records is however time consuming and complex. Today the challenge is to automatically convert data to knowledge, which frees the manpower to implement corrective or preventive action.

With the introduction of the digital recording technology, e.g., digital fault recorders (DFRs) at the moment engineers in power utilities have more data than can be processed and assimilated in the time available. However, analysis of disturbance records from the DFRs is becoming increasingly important and critical to prevent power failures, black-outs and the like. So, we propose an automated analysis system [1] for the automatic disturbance recognition and analysis, based on the real disturbance recordings obtained from the power network in South Africa.

In the direction towards an automated recognition-oriented task, we would first apply the abrupt changes detection algorithms to segment the fault recordings into different segments. Then we would construct the appropriate feature vectors for the different, specific segments; finally pattern-matching algorithm would be applied using those feature vectors to accomplish the disturbance recognition and analysis tasks [2].

2 Analysis of Disturbance Data

2.1 Introduction

In 1998, a 24 hours support service for ESKOM (South African power utility) National Control was introduced to supply operating personnel with information from disturbance records analysis with an aim to enhance operational decisions, immediately identify potential risk and improve response time to latent weaknesses or failures [3]. Since 1993 ESKOM is installing centralized per substation disturbance recorders on the transmission lines (currently installed at 136 substations). The DFRs are installed on the feeder bays, with an additional few installed on the Static Var Compensators (SVCs) [4]. The recorders monitor all voltages and currents and 30 selected protection operation outputs per line. The recorders are triggered by protection operation pulses and, some of them, by dv/dt (change of phase voltage). The recording duration varies from 2 to 12 seconds with scanning frequency of 2.5 kHz. The implementation of the X.25 communication facility was initiated in 1995 and presently all recorders are remotely accessible [5]. In line with the commissioning of new recorders the amount of mathematical analysis of recorded signals was continuously growing. Storage and retrieval of disturbance data became a real challenge (presently approximately 2000 records a year).

Presently semi-automatic software is available for data acquisition and storage in the performance database. Results from the analysis of the digital fault records are also captured in a database called 'TIPPS' (Transmission Integrated Plant Performance System) [1]. In the fully developed automatic system, mathematical analysis of all (presently known) patterns of incorrect behavior (disturbances) should be performed automatically and only a short message should be issued for the controllers (operating personnel) summarizing the required information and knowledge.

2.2 Disturbance Analysis Scheme

Fig. 1 shows the disturbance analysis scheme employed at the National Control, ESKOM, South Africa. In Fig. 1, the blocks in solid-lines indicate the existing systems, whereas the blocks in dotted-lines indicate the proposed automatic disturbance recognition and analysis systems.

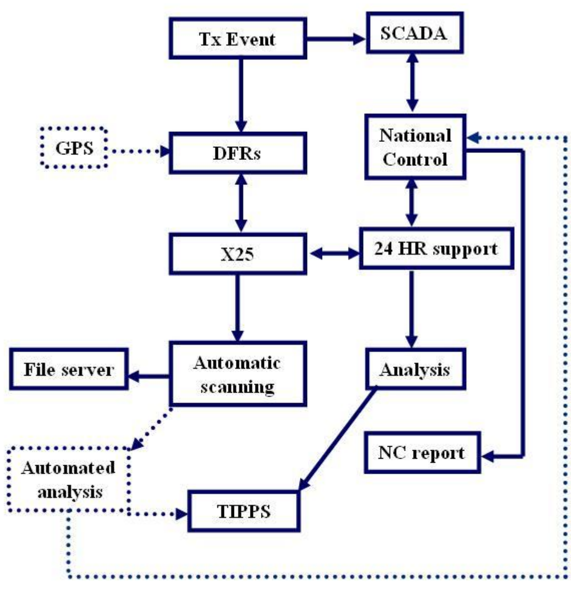

Fig. 1. Disturbance Analysis Scheme at ESKOM

As per Fig. 1, when an event (Tx-event) on the power transmission network occurs National Control (NC) will be informed via a SCADA (Supervisory Control And Data Acquisition) network and also the DFRs will be triggered. The protection engineers provide a 24-hour support through the analysis of these records. It is possible to download the fault record via the X.25 communication network. The protection engineer has to do a manual analysis to create a report for National Control. The manual analysis is cumbersome and takes a lot of time, typically from 1 hour to 10 hours or more, depending on the complexity and severity of the event. Additionally an automatic scanning PC downloads the records. They need to be saved manually at a file server. Results from the analysis of the digital fault records are also captured in the 'TIPPS' database [1]. Due to large amount of historical data available trend analysis on the performance of primary and secondary equipment can be done.

An automated analysis system (shown in dotted lines in Fig. 1) would be much faster, and it could be placed in two different ways. The more efficient way is to do the automated analysis direct at the substation and only to transmit a report to NC. This is the fastest way to do it but additional PC's and the communication infrastructure (for example a LAN) are needed. The other way is to run the automated analysis on a central PC. The disadvantage is that it takes much more time to download the whole record than to send a report. The big advantage is the cost factor because only one PC is needed and the communication network is much simpler. The automated analysis system should also be able to write the analysis results to the TIPPS database.

2.3 Existing Disturbance Analysis System

Majority of digital fault recorders in ESKOM are from Siemens: 'SIMEAS-R' and 'OSCILLOSTORE P531' recorders. 'SIMEAS R' comes with 16-bit resolution and a 12.8 kHz maximum scanning frequency per channel. There are two types of central unit: one with 8 analogue and 16 binary channels, and one with 32 analogue and 64 binary channels [5]. 'OSCILLOSTORE P531' comes with 8- and 12-bit resolution and a 5 kHz maximum scanning frequency. It has 31 Data acquisition units (DAUs) per central unit, i.e., 124 analogue or 992 binary data acquisition channels [5]. Every feeder uses 3 Data acquisition unit (DAU): 2 x ADAU (analogue data acquisition units used for 4 x voltage and 4 x current signals), and 1 x BDAU (binary data acquisition unit used for up to 32 digital signals) [5]. The 32 Binary values are either stored as a '0' or a '1' and indicates the status of a contact e.g., breaker auxiliary contact. Analogue values indicate the magnitude of an analogue signal (voltage or current) measured at a specific point in time.

Following the IEEE COMTRADE standard [6], the DFR recordings are provided as input to the existing semi-automatic fault analysis software which uses Discrete Fourier Analysis and Superimposed current quantities [5]. All the disturbance analysis are done manually which is quite complex and time-consuming process [5]. Also some information from the existing analysis system, especially the circuit breaker binaries are very often not complete, that is why they are not so trustworthy and need to be handled with care. A fault analysis system based only on the binaries should be avoided.

3 Automated Analysis System

3.1 Specification

The first requirement for the Automated Analysis System (AAS) is that it must be able to read a COMTRADE file [6]. The AAS must be able to automatically import the COMTRADE file from a user defined directory, do the analysis and produce the results in a format which can be viewed by any text editor. The distribution of the results should be done through any of the following media: fax, e-mail, SMS, print or Web [1]. The AAS must extract from the COMTRADE file the following information [1]:

- Faulted phase(s),
- Fault type,
- Total fault duration,
- Main 1 protection operating time,
- Main 2 protection operating time,
- Fault location,
- Fault resistance,
- DC offset,
- Breaker operating time,
- Auto re-close time.

Apart from the above the AAS must also determine and report on the following as described in [1]:

- Was the fault on the specific feeder?
- Did the main 1 relay operate?
- Did the main 1 relay operate correctly?
- Did the main 2 relay operate?
- Did the main 2 relay operate correctly?
- Was the main 1 permissive carrier signal sent, and was this correct?
- Was the main 2 permissive carrier signal sent, and was this correct?
- Was the main 1 permissive carrier received, and was this correct?
- Was the main 2 permissive carrier received, and was this correct?
- How did the breaker operate – 1 pole or 3 poles?
- Did the breaker auto re-close (ARC)?
- What was the magnitude of the fault current?
- What was the magnitude of the neutral current?
- What was the magnitude of the healthy phase currents during the fault?
- What was the depression in voltage on the faulted phase/s?
- What was the depression in voltage on the healthy phase/s?
- What were the dominant frequencies before and during the fault?
- Did any of the breaker poles re-strike?

3.2 System Overview

In the direction towards an automatic recognition-oriented task, we would first apply the abrupt changes detection algorithms on the fault recordings. This will segment the fault recordings into different event-specific segments, namely, pre-fault segment, after circuit-breaker opening, after auto-reclosure of the circuit-breakers. Then we would construct the appropriate feature vectors for the different segments; finally the pattern-matching algorithm would be applied using those feature vectors to accomplish the fault recognition and associated tasks [7].

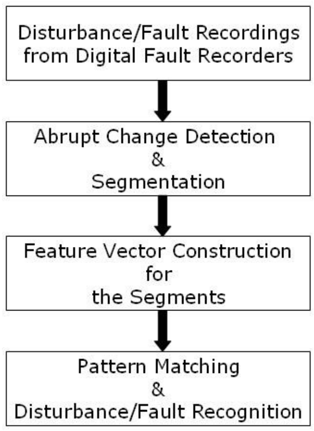

Fig. 2. Architecture of the Automated Analysis System

The complete architecture of the proposed automated analysis system is shown in Fig. 2 [7]. In Fig. 2, the architecture of the automated analysis system is a sequential top-down block diagram. Each of the blocks is described in the following sections.

4 Recordings from DFRs

DFRs are highly accurate recording instruments providing sampled waveform and contact data using relatively high sampling rate, typically above 5 kHz (a sample every 0.2 milliseconds). As per IEEE COMTRADE standard [6], each event shall have three types of files associated with it [7]. Each of the three types carries a different class of information: header (*.HDR), configuration (*.CFG) and data (*.DAT). Each record (row) in the data file (*.DAT) obtained from the ESKOM DFRs has 42 data items (columns): first column is the sample number, second column is the time in microseconds from the beginning of the record, next 8 columns are the 4 analogue voltage and 4 analogue current recordings, next 32 columns are the 32 binary points representing the contact changes [7]. Fig. 3 shows a sample record from a data file.

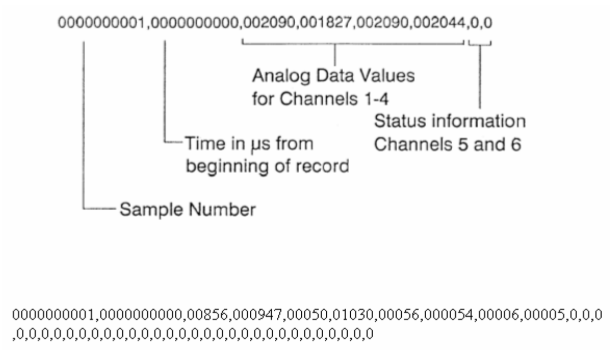

Fig. 3. Digital Fault Recorder data file format

5 Abrupt Change Detection based Signal Segmentation

Detection of abrupt changes in signal characteristics is a much studied subject with many different approaches. It has a significant role to play in failure detection and isolation (FDI) systems and segmentation of signals in recognition oriented signal processing [8]. Many of these signals are quasi-stationary in nature i.e., these signals are composed of segments of stationary behavior with abrupt changes in their characteristics in the transitions between different segments. It is important to find the time-instants when the changes occur and to develop models for the different segments during which the system does not change [2].

Segmentation of the fault recordings by detecting the abrupt changes in the characteristics of the fault recordings, obtained from the DFRs of the power network in South Africa, is the first step towards automatic disturbance recognition and analysis. Abrupt change detection algorithms collectively segment the fault recordings into different event-specific segments, namely, pre-fault segment, after initiation of fault, after circuit-breaker opening, after auto-reclosure of the circuit-breakers [7].

Ukil & Zivanovic studied the different technologies for abrupt change detection in a comparative manner in [2] and categorized the techniques broadly as:

- Simple methods,
- Linear model-based approach,
- Model-free approach,
- Non-parametric approach.

The authors have already presented detail description of the abrupt change detection using the wavelet transform and threshold checking in [9].

We apply the Multiresolution Signal Decomposition (MSD) [9] technique and Quadrature Mirror Filter (QMF) [9] banks to decompose the fault signals from the DFRs into localized and detailed representation in the form of wavelet coefficients. Daubechies 1 and 4 wavelets [9] are used as the *mother* wavelets. After transforming the original fault signal using the mother wavelets and discrete wavelet transform, we obtain the smoothed and detailed versions. The detailed version, called the wavelet transform coefficient, is used for threshold checking to estimate the change time-instants.

Fig. 4 shows the segmentation result for the fault signal, sampled at a sampling frequency of 2.5 kHz, obtained from the DFRs during a phase-to-ground fault. In Fig. 4, the original DFR recording for the current during the fault in the RED-Phase is shown in the top section, wavelet coefficients for this fault signal (in blue) and the universal threshold (in black, dashed) are shown in the middle section and the change time-instants computed using the threshold checking (middle section) followed by smoothing filtering is shown in the bottom section. The signal segments effectively indicate the different events during the fault, e.g., segment A indicates the pre-fault section and the fault inception, segment B indicates the fault, segment C indicates opening of the circuit-breaker, segment D indicates auto-reclosing of the circuit-breaker and system restore.

The authors also proposed system identification based approach for abrupt change detection in [10], which uses recursive identification method. In the proposed Recursive Identification technique, several parallel Kalman filters are used to estimate the signal parameters. Each of them corresponds to a particular assumption about when the system actually changed. The relative reliability of these assumed system behaviors is constantly judged, and unlikely hypotheses are replaced by new ones.

The proposed wavelet transform and recursive identification techniques are effective for about 60% of the disturbance signals, having distinct abrupt changes in the signal model parameters. However, about 40% of the disturbance signals do not show

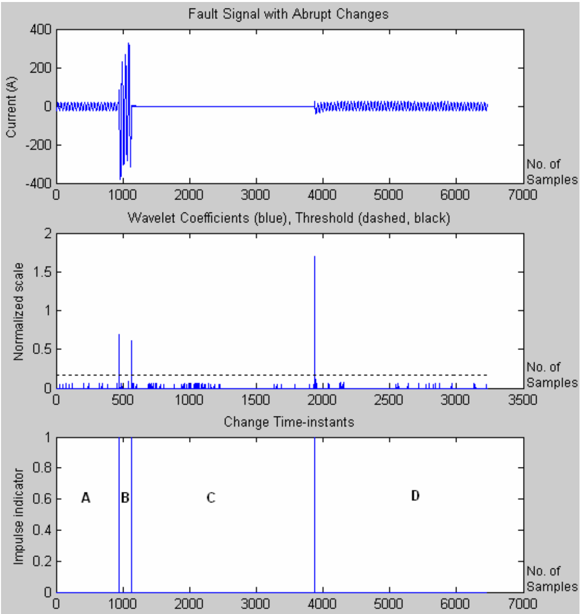

Fig. 4. Segmentation of the RED-Phase current signal using Wavelet Transform technique

distinct abrupt changes in the signal parameters [7]. In those cases, we have to apply adaptive abrupt change detection, based on adjusted 'Haar' wavelet technique [11].

6 Feature Vector Construction

The main objectives of this step are as follows.

- Development of the parameter identification techniques for various models.
- Development of parameter identification technique in presence of non-linearity, e.g., case with the slow time-varying amplitude and frequency.
- Feature extraction from the other sources apart from analogue signals.

Practical recorded signal is corrupted with noise and nuisance components (higher frequencies due to wave transients and measurement system bias). Link between the system model and the signal model could be established through the State Space Theory. To filter noise and bias, extended version of the Structured Total Least Squares method [12] will be used.

To include network non-linearities, the system can be modeled using the system of linear differential equations perturbed with nonlinearity (quasi-linear system). Here in the modeling we can use Averaging approximation technique (only the first order approximation) called in engineering the Describing Function method [13].

The signal model has the same structure as described above but the parameters are slow time-varying. Time varying version of the Structured Total Least Squares method should be adopted here. Higher harmonics associated with a non-linearity will be treated as nuisance components and filtered out in the estimation process. Link between the time-varying signal model and the system model will be established using the Averaging Theory [13].

Other sources for feature extraction process are binary disturbance records (opening & closing of various contacts associated with recorded event) and expert knowledge about disturbances provided by ESKOM specialists. Zivanovic [14,15,16] also proposed a frequency estimation algorithm based on local polynomial approximation technique for use in the feature vector construction. The semi-parametric estimation approach for the feature vector construction is depicted in Fig. 5.

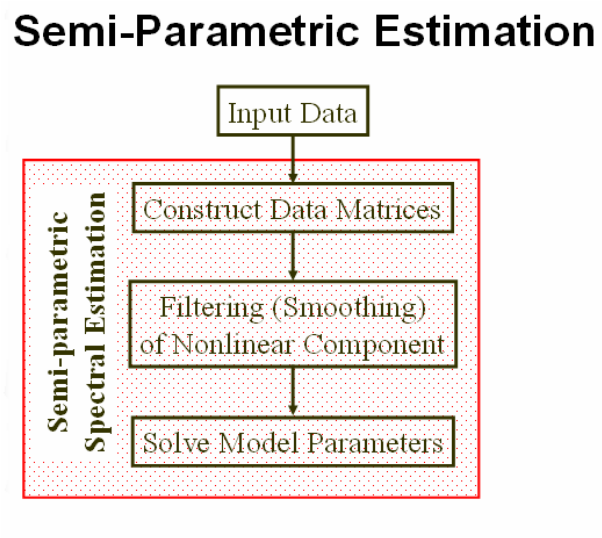

Fig. 5. Feature vector construction using semi-parametric approach

7 Pattern Matching and Disturbance Recognition

The main objectives of this step are as follows.

- The best set of features (obtained from parameter identification process and other sources) should be selected to represent disturbances.
- Adopting the classification algorithm and training using recorded data and human expertise.
- The simple demonstration prototypes of the following analysis algorithms will be developed: Fault location algorithm, Analysis for resonant conditions in the system with

trapped energy, Protection and control system performance analysis, Electromechanical oscillation and system stability analysis.

Development in this step will rely on the available techniques from the Statistical Learning field [17]. The classification task should deal with data of mixed type (continuous values, breaker open & close, expert knowledge etc).

Keller, Henze & Zivanovic proposed a Support Vector Machine (SVM) based fault classifier in [1]. SVM is a training algorithm for learning classification and regression rules from data, first introduced by Vapnik in 1960's [17]. The SVM-based fault classifier shall separate ground faults from non-ground faults. Detail mathematical description of the fault classification system can be found in the practical training report by Henze [1].

The input feature space is two-dimensional and consists of the magnitude of the 50 Hz component of the neutral current (X_1) and the zero sequence Voltage (X_2). Typically 10 ground faults and 10 phase-to-phase faults are used as training data [1]. For the output, $Y_i = 1$ means ground fault and $Y_i = -1$ means none ground fault. After training the SVM classifier, another data set is used to test it. Typical test data set consists also of 10 ground and 10 non-ground faults [1]. Fig. 6 shows the algorithm of the SVM fault classifier as a flowchart.

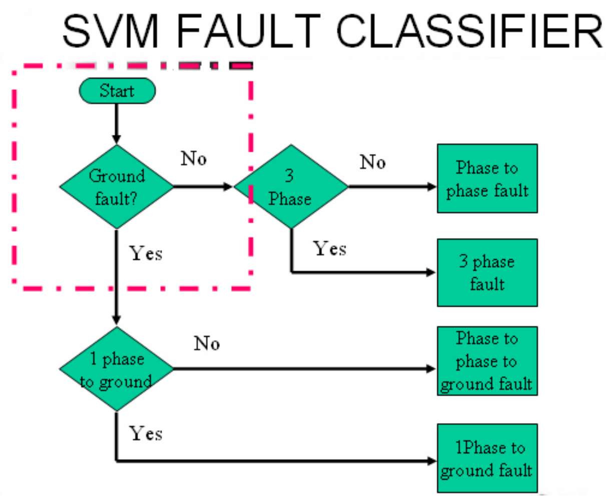

Fig. 6. SVM-based fault classifier algorithm flowchart

8 Commercial Implementation

We also propose an effective commercial implementation of the whole project. The automatic analysis system would be available for use via the Application Service Provider (ASP) technology over the Internet with direct and indirect modes [18].

9 Conclusion

Automatic analysis of disturbance data following the approach of signal segmentation, feature vector construction and pattern matching technique is quite critical for secure and reliable power supply. The automatic analysis system proposed in this paper would perform the whole analysis within five minutes, overtaking much slower manual analysis. The proposed approach has been implemented and tested using real disturbance records from the power network in South Africa. The automatic analysis system will be commercially implemented as application service provider solution over the Internet.

References:

[1] P. Keller, C. Henze, R. Živanović, Automated Analysis of Digital Fault Records: A Utility Perspective, *SAUPEC Conf.*, Johannesburg, South Africa, Jan 2005.
[2] A. Ukil, R. Živanović, Detection of Abrupt Changes in Power System Fault Analysis: A Comparative Study. *SAUPEC Conf.*, Johannesburg, South Africa, Jan 2005.
[3] A. Bartylak, Application of Disturbance Recorders as Near Real Time Information Support for National Control in ESKOM, *DPSP Conf.*, Amsterdam, Netherlands, 2002.
[4] E. Stokes-Waller, Automated Digital Fault Recording Analysis on the Eskom Transmission System, *S. African Conf. on Power System Protection*, South Africa, 1998.
[5] E. Stokes-Waller, P. Keller, Power Network and Transmission System based on Digital Fault Records, *S. African Con. on Power System Protection*, S. Africa, 1998.
[6] *IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems*, IEEE Standard C37.111-1991, Version 1.8, February 1991.
[7] A. Ukil, Application of Abrupt Change Detection in Automatic Disturbance Recognition in Electrical Power Systems, Ph.D. dissertation, Dept. Math. Tech, Tshwane Univ. of Tech, Pretoria, South Africa, 2005.
[8] M. Basseville, I.V. Nikoforov, *Detection of Abrupt Changes–Theory and Applications,* Englewood Cliffs, NJ : Prentice-Hall, 1993.
[9] A. Ukil, R. Živanović, Abrupt Change Detection in Power System Fault Analysis using Wavelet Transform, *Int. Power Systems Transient Conf.*, Montréal, Canada, Jun 2005.
[10] A. Ukil, R. Živanović, The Detection of Abrupt Changes using Recursive Identification for Power System Fault Analysis, *Electric Power Systems Research, Elsevier*. (Submitted)
[11] A. Ukil and R. Živanović, Adjusted Haar Wavelet for application in the Power Systems Disturbance Analysis, *EURASIP Journal of Applied Signal Processing*. (Submitted)
[12] R. Živanović, Analysis of Recorded Transients on 765kV Lines with Shunt Reactors. *IEEE Power Tech*, St. Petersburg, Russia, 2005.
[13] A. Geleb, W.E.V., Velde, *Multiple-input Describing Functions and Nonlinear System Design*, McGraw-Hill, 1968.
[14] R. Živanović, Nonparametric Frequency Estimation for Power System Applications, *IEEE Porto Power Tech*, Porto, Portugal, 2001.
[15] J.A. Jordaan, R. Živanović, Nonparametric Time-Varying Phasor Estimation in Power Systems by making use of Non-quadratic Criterion, *IEEE AFRICON*, South Africa, 2002.
[16] R. Živanović, Frequency Estimation Algorithm based on Local Polynomial Approximation. *UPEC Conf.*, Leicester, UK, 1999.
[17] V. Vapnik, *The Nature of Statistical Learning Theory*, New York: Springer, 1995.
[18] A. Ukil, R. Živanović, Practical Approaches in Application Service Provider: A Comparative Study, *2nd World Congress on Lateral Computing*, Bangalore, India, Dec 2005.