Knowledge and Model Based Reasoning for Power System Protection Performance Analysis

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Abstract

Technological advances within the field of power systems has led to engineers, at all levels, being confronted with an ever increasing amount of data to be analysed. This coincides with greater pressure on engineers to work more efficiently and cost effectively, due to the increasingly competitive nature of the electricity supply industry. As a result, there is now the requirement for *intelligent systems* to interpret the available data and provide *information* which is relevant, manageable and readily assimilated by engineers.

This thesis concerns the application of intelligent systems to the data interpretation tasks of protection engineers. An on-line decision support system is discussed which integrates two expert system paradigms in order to perform power system protection performance analysis. Knowledge based system techniques are used to interpret the data from supervisory, control and data acquisition systems, whereas a model based diagnosis approach to the comprehensive validation of protection performance, using the more detailed data which is available from fault records or equivalent, is assessed.

Such a decision support system removes the requirement for time consuming manual analysis of data. An assessment of power system protection performance is provided in an on-line fashion, quickly alerting the engineers to failures or problems within the protection system. This improves efficiency and maximises the benefit of having an abundance of data available.

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Acknowledgements

I would like to thank Professor Jim McDonald in the Centre for Electrical Power Engineering, at the University of Strathclyde, for all of his guidance and support. My research benefited from his enthusiasm for the work and his willingness to discuss my ideas (and rantings!). I hope that he is impressed that this thesis does not run to five hundred pages, and recognises that the monster was caged during the writing process.

I extend my gratitude to ScottishPower Power Systems for funding this research. Furthermore, I am grateful to Ron Mather, Marshall Burt, Tom Cumming, Alan Young and Jim Farrell for their contributions to the work, both technical and otherwise.

Thanks to Stewart Bell and Adam Dysko for the very significant contributions that they have made to this project. I am grateful for their opinions and ideas, but most of all I am grateful that they have tolerated me for so long.

My thanks is extended to everyone in the Intelligent Systems and Protection Group for their helpful comments, discussions, advice and friendship. An extra thanks goes to Alan Moyes and Zac Richardson. We started our research "lives" together and helped each other through the initial "dazed and confused" stages of a PhD.

Without the enthusiasm, guidance, support and encouragement of my parents I would never have achieved this degree. I cannot thank them enough. Also, thanks to my brother Gordon for always reminding me that having a PhD doesn't mean that I can "do anything useful".

Finally, I wish to thank everyone outwith my working life who tried to keep me sane (with or without success, you decide) over the last three and a half years.

Glossary of Terms

AFRA	Automatic Fault Record Analysis
AI	Artificial Intelligence
ANN	Artificial Neural Network
APEX	Alarm Processing Expert System
ARCHON	Architecture for Cooperative Heterogeneous On-line Systems
ARTIST	Advanced Reasoning Tools for Model Based Diagnosis of Industrial Systems
ATMS	Assumption based Truth Maintenance System
CBR	Case Based Reasoning
CHECK	Combining Heuristic and Causal Knowledge
CT	Current Transformer
DART	Model based diagnostic system by Genesereth
DSS	Decision Support System
GA	Genetic Algorithm
GDE	General Diagnostic Engine
GDE+	Extended GDE by Struss and Dressler
IDMT	Inverse Definite Minimum Time
KBS	Knowledge Based System
MBD	Model Based Diagnosis
MBR	Model Based Reasoning
RESPONDD	Rulebased Expert System for Power Network Disturbance Diagnosis
SCADA	Supervisory, Control and Data Acquisition
Sherlock	Model based diagnostic system by de Kleer and Williams
VT	Voltage Transformer

Chapter 1

Introduction

1.1 Introduction to Research

As the electrical power industry witnesses continuing technological advances in the areas of Supervisory, Control and Data Acquisition (SCADA) systems, Remote Telemetry Units (RTU) and telecommunications, an ever increasing amount of data is available to utility engineers. Unfortunately, increased data does not always mean improved understanding of the present state of the power system, especially during power system disturbances where voluminous data can overwhelm the engineers. Consequently, the advances in data gathering and presentation must be complemented by intelligent data interpretation systems, converting *data* into appropriate *information* for engineers.

The need for such intelligent data processing has fuelled extensive research concerning the application of Artificial Intelligence (AI) techniques to electrical power systems. Indeed, paradigms investigated range from artificial neural networks (ANN) and genetic algorithms (GA) to expert systems [1] [2].

Expert systems have been applied to many tasks within the electricity supply industry [3] [4] [5]: network control; network restoration; fault diagnosis; maintenance scheduling; design; plant monitoring. Much of the work in this area has concentrated upon offering expert systems for centralised functions, either within distribution system, transmission system or power station control centres. However, in recent years the research community has witnessed the inception of more forward looking applications of expert systems within the realm of power systems. One such field is the distribution of *intelligence* throughout the power system network. This can be to the substation level, or indeed bay level within a substation. In fact, this is an aspect of the investigations into coordinated control and protection schemes [6].

The research reported in this thesis concerns the design of a decision support system (DSS) for utility protection engineers, employing knowledge based system and model based reasoning techniques (which are expert system paradigms). The use of the term "decision support system" reflects the fact that this intelligent analysis tool does not remove the autonomy of the engineers. Such a system is designed to aid their every day analyses. The knowledge based system module within the DSS will be shown to offer effective intelligent interpretation of SCADA system alarms. The DSS discussed in this thesis complies with the concept of distributing automated intelligent systems throughout electricity utilities. In this case, intelligent on-line data analysis is being offered at the Corporate Headquarters level to a design and analysis unit.

Significant previous research into the use of expert systems for on-line alarm processing and fault diagnosis produced the intelligent systems APEX (Alarm Processing EXpert system) [7] and RESPONDD (Rule-based Expert System for POwer Network Disturbance Diagnosis) [8], which interpret SCADA system alarms. Both intelligent systems were targeted at operators within control centres for electrical distribution/transmission networks. These systems provided the base, with appropriate tailoring, upon which the knowledge based module of the DSS was built.

A major aspect of the research reported in this thesis is the enhancement of the functionality of the DSS through model based reasoning (MBR), and in particular the subfield of model based diagnosis (MBD). This is a powerful AI reasoning paradigm which forgoes the traditional expert system approach of encoding fault models or heuristics into some form of knowledge base. MBD utilises models of correct behaviour for diagnostic purposes. The technique investigated is consistency based diagnosis. Prediction of expected device/system behaviour is achieved via the models, the output from which is then compared to the actual (observed) behaviour. Discrepancies between the predictions and observations are used to diagnose possible faults. This thesis will demonstrate that such an approach can be utilised to validate and diagnose the operation of power system protection schemes, using the detailed data available from fault recorders and modern microprocessor relays with inbuilt fault recording facilities. Hence, the complete DSS will interpret both SCADA system alarms and fault records.

In terms of the novelty of the research undertaken, three main contributions can be identified :

- **Distributing intelligent systems within the corporate framework.**

  The application itself is novel in that the DSS provides a corporate design and analysis group (protection engineers) with an intelligent analysis tool. As previously discussed, this is a departure from the traditional role of such systems at the control centre.

- **Model based reasoning for protection system validation and diagnosis.**

  Model based reasoning, and the subfield of model based diagnosis, have become very active areas of research within the AI community. However, much of this research has concerned the logical foundations [9] and reasoning processes required for efficient model based diagnosis [10] [11] [12]. As such, there has been limited application of this paradigm to a variety of engineering domains. Most case studies are directed towards the diagnosis of digital circuits.

  The research described in this thesis investigates such techniques for the analysis of power system protection performance, and as such offers an electrical engineering application to the domain of MBD. This entails selecting which facets of MBD are appropriate for utilisation within the DSS being developed, and the relevant merits of integrating MBD with other intelligent data interpretation systems. Additionally, the case studies discussed in this thesis will highlight the effective usage of detailed analogue (quantitative) data from fault records by the model based diagnostic mechanism. As such, the wider scope of

MBD is addressed through this research.

- **Integration of model based diagnosis and knowledge based systems within the DSS.**

  Given that the DSS comprises of both knowledge based and model based modules, it is essential that these are integrated and coordinated effectively. Therefore, an important aspect of the research being discussed is an appropriate integration strategy for the different methodologies used within the DSS. This is a significant issue as the AI/applied AI community strive towards the realisation of ***second generation expert systems*** [13], where multiple reasoning paradigms are combined within a single intelligent system. This permits the most effective technique to be applied at each stage of the reasoning process.

1.2 Justification for Research

The role of ScottishPower's protection engineers is to design, analyse and maintain protection schemes for the transmission system. After a power system disturbance protection engineers must determine the following points : Has there been a genuine disturbance in the power system? Have the relevant protection schemes operated correctly? Do the relevant protection schemes require to be replaced/redesigned/reset? To perform the analysis, SCADA system alarms are utilised. Traditionally, this data is provided by the control centre engineers in paper format. Additionally, the protection engineers may receive a phone call indicating some disturbance is taking place. Unfortunately, there can be a significant delay between the actual disturbance and the protection engineers receiving the appropriate data from the control centre. Following any significant power system event or disturbance (such as multiple faults being experienced under storm conditions) voluminous data can be produced by SCADA systems (e.g. during one week of storms, at one stage approximately eleven thousand alarms were received during a seventeen hour period). In addition, more detailed analyses of protection performance are carried out, using the data available from fault recorders or modern microprocessor relays with in-built storage capabilities.

The delay between the actual event and receipt of the relevant SCADA system alarms is a data availability problem. This can be eradicated by implementing a telecommunications "backbone" to offer on-line availability of the alarms, such as the network commissioned by ScottishPower in the course of this research (Figure 1.1). This also offers access to fault recorder data via modem links.

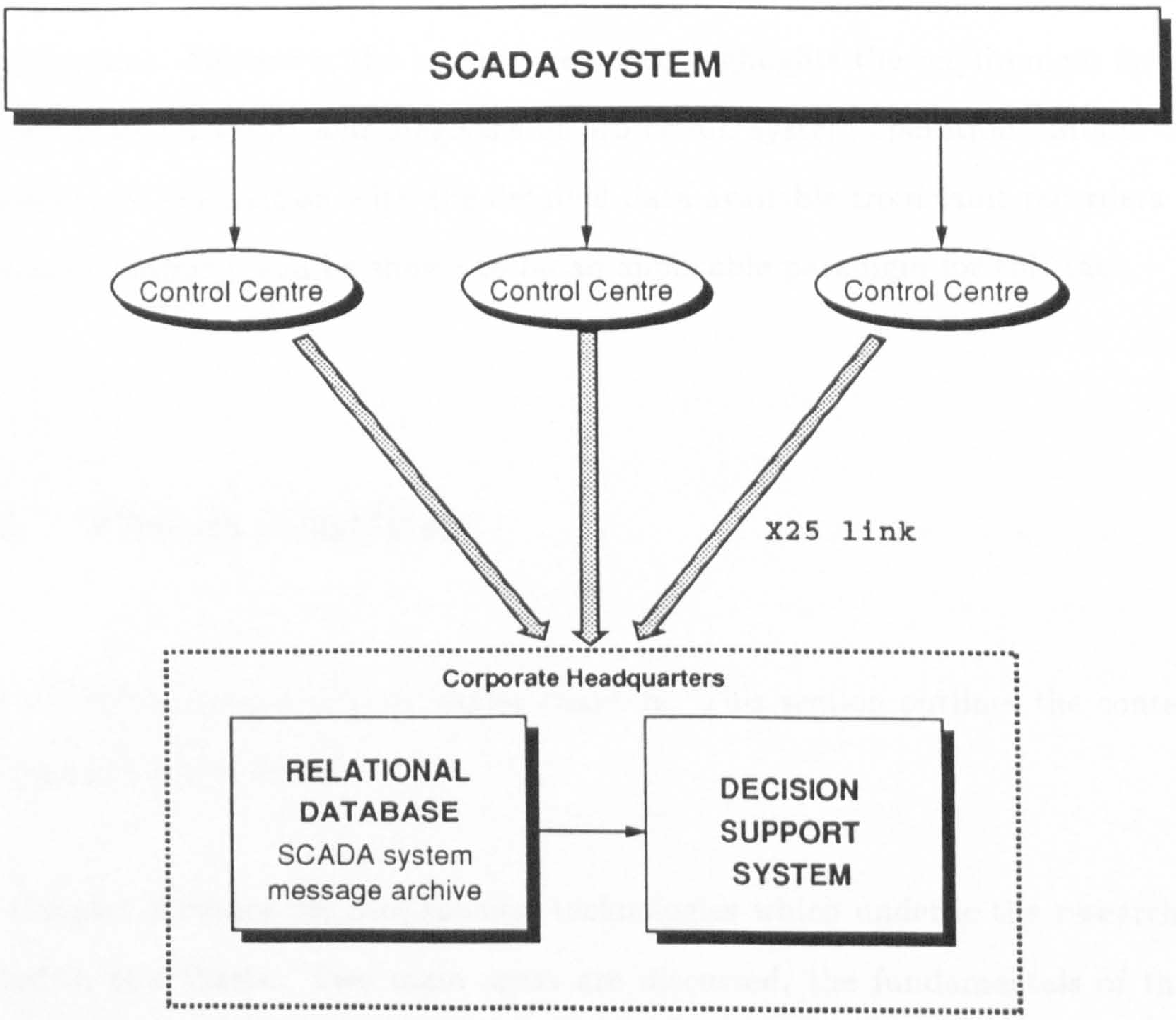

Figure 1.1: Telecommunications "backbone".

Three control centres (Hamilton, Yoker and Dewar Place) are used as data collectors for the communication links to the corporate headquarters. The incoming messages are stored within a relational database. This facilitates electronic archiving and browsing of historical power system events, while offering on-line access to SCADA system alarms for protection engineers. Furthermore, it provides the necessary SCADA system messages for the knowledge based module within the DSS.

The telecommunications network addresses the issue of data availability. Nevertheless, there remains the problem of data interpretation, especially under conditions of voluminous data. As a result of this problem, the research reported within this thesis concerns the design of a decision support system for protection engineers. The DSS is intended to overcome the data interpretation issue. The first aspect of this is the interpretation of SCADA system alarms. It will be demonstrated, through this thesis, that a two tiered expert system approach to SCADA system alarm analysis is appropriate. Moreover, the research reported highlights the requirement for more comprehensive analysis and diagnosis of protection system operation. Model based reasoning, in conjunction with the detailed data available from fault recorders (and equivalent devices), will be shown to be an applicable paradigm for this task.

1.3 Thesis Outline

The thesis is arranged into six major chapters. This section outlines the content of the chapters which follow.

Chapter 2 covers the fundamental technologies which underlie the research presented in this thesis. Two main areas are discussed, the fundamentals of the application domain and the fundamentals of expert systems. In the application domain sections, power systems and power system protection are discussed. Following this, expert systems are introduced, covering the key techniques and terminology employed. Chapter 2 is not intended to be exhaustive, but it provides the context for the research presented in the thesis. For completeness, bibliographies are provided to indicate relevant texts which discuss both areas in greater detail.

In Chapter 3 the requirement for decision support facilities for protection engineers is presented. This viewpoint is developed through an analysis of their role and the data analysis problems which they encounter. Through discussion of these topics, the functionality of a decision support system is specified. This will interpret both SCADA system data and fault records. The remainder of Chapter 3 covers the knowledge based interpretation of SCADA system data within the decision support system. A case study is provided. This chapter is supplemented by Appendix A, which covers in detail the two intelligent systems used within the knowledge based module of the decision support system. Chapter 3 concludes by indicating the need for comprehensive validation of protection performance, based on fault records or equivalent.

Chapter 4 discusses this issue in detail. The model based diagnosis expert system paradigm is proposed as an appropriate methodology to adopt. Model based diagnosis is discussed, resulting in the adoption of the consistency based diagnostic technique. As a feasibility study, a number of case studies concerning consistency based validation and diagnosis of protection are presented. These cover unit, distance and overcurrent protection schemes. Based on the case studies, an assessment of the possible utilisation of this technique, within the DSS, is given. This includes the benefits of adopting it and the future research directions which a model based technique indicates.

Having considered the knowledge based and model based modules in isolation, Chapter 5 discusses the issue of integrating the modules. The interaction between the two modules is demonstrated through a case study of their operation within the DSS. This leads to the specification of immediate and future operational requirements. A methodology and architecture for integration are proposed, with the future research required to fully develop the DSS being highlighted. This chapter concludes by considering the possible uses of such a DSS.

Chapter 6 completes the thesis by presenting the conclusions which resulted from the research. In addition, future work is suggested which will allow the concepts within the thesis to progress.

1.4 Associated Publications

The following publications have arisen from the research detailed in this thesis :

1. S.D.J. McArthur, J.R. McDonald, G.M. Burt, R. Mather and S.M. Burt, "The Use of Expert Systems for the Analysis of Power System Protection Performance", 28th Universities Power Engineering Conference (UPEC), Staffordshire, England, Volume 1, pp. 117-120, September 1993.
2. S.D.J. McArthur, J.R. McDonald and G.M. Burt, "Intelligent protection performance monitoring", IEE Power Division Colloquium on Expert systems in the field of protection and control, Digest No: 1993/193 pp. 4/1-4/3, Tuesday 26th October 1993.
3. S.D.J. McArthur, J.R. McDonald, R.Mather and S.M. Burt, "An Expert System for On-line Analysis of Power System Protection Performance", Expert Systems 94 Conference (ES94), Applications and Innovations in Expert Systems II, pp. 125-142, December 1994.
4. S.D.J McArthur, J.R. McDonald, S.C. Bell and G.M. Burt, "Expert systems and model based reasoning for protection performance analysis", IEE Power

Division Colloquium on Artificial Intelligence applications in power systems, Digest no: 1995/075, pp. 1/1 - 1/4, Thursday 20th April 1995.

5. S.D.J. McArthur, J.R. McDonald, S.C. Bell, G.M. Burt, R. Mather and S.M. Burt, "The extension of corporate communications networks to realise intelligent data analysis : A case study providing protection system performance analysis", Cigre Symposium on Integrated Control and Communication Systems, Helsinki, Finland, August 1995, paper 600-05.

6. S.D.J. McArthur, A. Dysko, J.R. McDonald, S.C. Bell, R. Mather and S.M Burt "The Application of Model Based Reasoning within a Decision Support System for Protection Engineers", IEEE Power Engineering Society 1996 Winter Meeting, Baltimore, Maryland, 21-25 January, 1996 (96 WM 333-5 PWRD). Also to be published in IEEE Transactions on Power Delivery.

7. S.D.J. McArthur, S.C. Bell, J.R. McDonald, R.Mather and S.M. Burt, "Knowledge and Model Based Decision Support for Power System Protection Engineers", Proceedings of the International Conference on Intelligent Systems Applications to Power Systems (ISAP'96), pp. 215-219, 1996.

8. S.D.J. McArthur, S.C. Bell, J.R. McDonald, R.Mather, S.M. Burt and T. Cumming, "Decision Support for the Interpretation of Power Network Data of Relevance to Protection Engineers", to be published at Cigre 1996 Conference, Paris.

Other publications on related topics are :

1. G.M. Burt, A. Moyes, S.D.J. McArthur and J.R. McDonald, "Intelligent Systems for the Operation and Control of Electrical Power Systems and Plant", First International Conference on Electrical Power Engineering and Water Resource Management, Peshawar, Pakistan, November 1994.

2. J.R. McDonald, G.M. Burt, S.D.J. McArthur, S.C. Bell, I.M. Elders, E.K. Han, "Proposed Architecture for Integrated Decision Support Within Second Generation Distribution Management Systems", Distribution Automation and Demand Side Management, Singapore, pp. 27-35, 1995 (DA/DSM'95 Asia).

Chapter 2

Fundamentals

2.1 Chapter Overview

This chapter introduces the fundamental concepts underlying both the application domain and expert systems in terms of the research being reported. It is not intended for this chapter to be an exhaustive exposition of these areas, but that it covers the essential concepts required to put into context the research discussed later.

2.2 Fundamentals of the Application Domain

2.2.1 The power system network

The purpose of a power system network is to transport electrical energy, both economically and reliably, from the generating source to the customers while meeting demand. This is achieved through the interconnection of overhead lines, cables, transformers, busbars and switchgear which constitute the electrical network.

The transmission network carries the output from the generating stations to the areas where it must be distributed to customers. Typically, these are remote from one another due to the constraints of siting a power station (i.e. the location is selected with factors such as safety, cooling and transport of fuel as priorities). In the United Kingdom transmission occurs at the voltage levels of 400kV and 275kV. The transport to customers is effected by the distribution network, which carries electricity at the 132kV, 33kV and 11kV voltage levels.

In addition to the aforementioned electrical network, there are further subsystems within the power system network including control, operation, monitoring, the SCADA system and the protection system. The latter of these are of greatest concern to the research work reported in this thesis.

Given the activity which takes place on the power system network, the role of the Supervisory, Control and Data Acquisition (SCADA) system is twofold. Firstly, it provides data regarding the present status of the network (circuit breaker status, protection operations, measurement indications, etc.) to operators at the control centre. Moreover, this data can be made available to other interested engineers as is the case for the research being reported in this thesis. Secondly, it allows operators to control plant items remotely, such as opening/closing isolators or circuit breakers.

The remainder of this section is devoted to the final subsystem, namely the protection system.

2.2.2 Power system protection

Faults within an interconnected electrical power network result in abnormal currents and voltages being produced. The occurrence of faults is common and can be due to the effects of insulation aging, lightning, human error, device failure, etc. Unfortunately, fault conditions within the electrical power network can cause thermal and mechanical damage to plant, in addition to the possible loss of synchronism. Therefore, it is essential that such anomalous conditions are removed from the network as quickly as possible. The protection system automatically detects and measures abnormal current and voltage conditions and, when detected, opens the appropriate switchgear to isolate the fault. In summary, the operation of protection and consequent opening of circuit breakers serves two main functions :

1. The isolation of faulty equipment to allow the remainder of the power system to operate successfully.
2. The limitation of damage to equipment as a result of overheating and mechanical forces.

2.2.2.1 Qualities required of power system protection

When discussing power system protection a number of essential qualities must be taken into consideration :

- **Selectivity/Discrimination**

  The effectiveness of the protection in isolating only the faulty section of the network is important.

- **Stability**

  The protection must not operate for faults outwith the protected zone, or for expected system transient behaviour.

- **Speed of operation**

  Faults must be cleared in the quickest time possible, since the longer the exposure to abnormal currents and voltages the greater is the damage to equipment. Furthermore, it is important that isolation occurs before synchronous generators lose synchronism with the rest of the network.

- **Sensitivity**

  Sensitivity is the ability of the protection to recognise a fault when the power system condition may differ only slightly from healthy conditions.

- **Reliability**

  Of obvious importance is the fact that protection systems should not maloperate.

In addition to the above technical considerations, there are economic factors which must be taken into account. The actual protective devices employed can be relatively simple and inexpensive (e.g. fuses, miniature circuit breakers or electromechanical overcurrent relays), or sophisticated and expensive (e.g. microprocessor or numerical based relays with high frequency communication capabilities using the power line as a carrier). Therefore, a decision has to be made on the complexity of protection to be applied at any section of the electrical network. However, increased complexity of protection usually means increased cost. This decision depends upon two facts :

1. The cost of faults.[1]
2. The desired level of supply security.

The decision on which protective devices to use is one of protection economics. At the consumer level individual items of equipment or circuits are protected by fuses and miniature circuit breakers. For distribution networks security of supply is a priority. Therefore, redundancy is introduced through the the utilisation of ring systems and by duplication of feeders. As a result of the many feeders, transformers, etc. that constitute the distribution network, the economic implications of protection override the technical ones. This means that less expensive protection is used, provided that the basic safety requirements are satisfied. For example, extensive use is made of automatically reclosing circuit breakers and protection systems based on

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[1] Fault costs comprise the potential cost of plant damage plus the costs associated with customer disconnection and loss of goodwill as well as commercial penalties which are becoming prevalent in the new power supply industry environment.

current measurement only. Within the transmission network the equipment being protected is expensive and security of supply is vital. Thus, complex (and therefore expensive) protection systems are justified. At the transmission level protections are typically duplicated to offer two main and backup protection operations. These can be termed first main, second main and backup protection.

2.2.2.2 Protection subsystems

Protection systems have three main subsystems :

1. Devices for measuring power system conditions. That is, current transformers (CTs) and voltage transformers (VTs).
2. Relays which determine if a fault condition is being experienced through measurement and comparison (based on CT and VT measurements) and consequently trip the associated switchgear.
3. Circuit breakers and other switchgear which isolate the faulted part of the network, when triggered by the appropriate relay(s).

2.2.3 Examples of protection schemes

The arrangement and specification of the protection subsystems depends upon the functionality required. Protection functionality can be partitioned into two main categories : *unit protection* and *non-unit protection.*

Unit protection schemes are designed to isolate a distinct area or item of plant within the power system network. Isolation will occur when an internal fault (a fault within the distinct area or item of plant being protected) is experienced, otherwise the protection will remain inoperative for external faults (and normal "healthy" power system conditions). Non-unit protection schemes monitor the power system conditions at a relaying point. This type of protection will operate to disconnect faults occurring in the surrounding power system should the current/voltages be at such a level as to cause relay operation.

The following sections describe the principles behind certain protection schemes.

2.2.3.1 Unit protection schemes

Unit schemes protect sections of the power system as independent regions, without reference to other areas of the network. In general, this involves the measuring of fault currents at each end of the protected zone and the communication of information between the protection equipment.

The basis of many unit protection arrangements, for feeders and other items of plant, are differential systems. In differential systems the underlying requirement is to determine the relative direction of the fault current, which can only be expressed on a comparative basis.

One arrangement providing such differential unit protection is shown in figure 2.1. Similar current transformers at each end of the protected zone are interconnected by an auxiliary *pilot* circuit. For out of zone faults and normal power system conditions, the current flowing through the zone causes secondary current to circulate round the pilot circuit without any current being produced in the relay. However, an in-zone (or internal) fault will cause secondary currents with opposing relative phase. The summated value of these will flow in the relay, causing operation. This is termed a differential circulating current protection scheme.

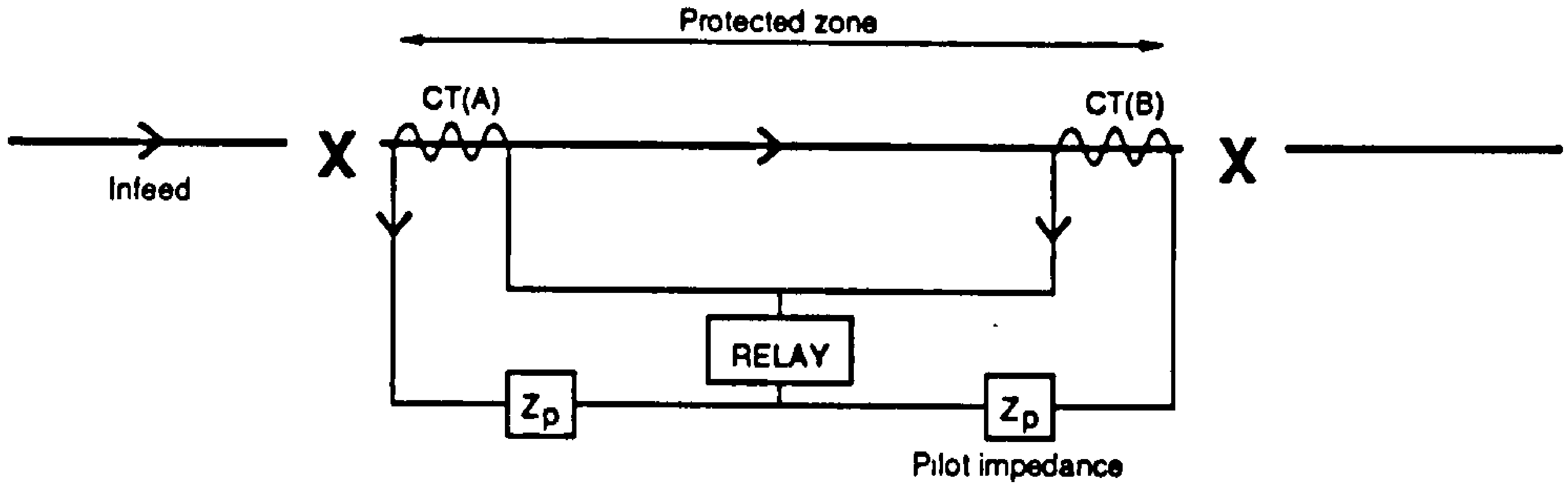


Figure 2.1: Circulating current differential protection scheme.

An alternative to the differential circulating current arrangement sees the CT secondary windings being opposed for through-fault conditions. Therefore, no current flows in the series connected relays. An in-zone fault leads to a circulating current condition and hence the relays operate (figure 2.2). This is known as a balanced voltage scheme.

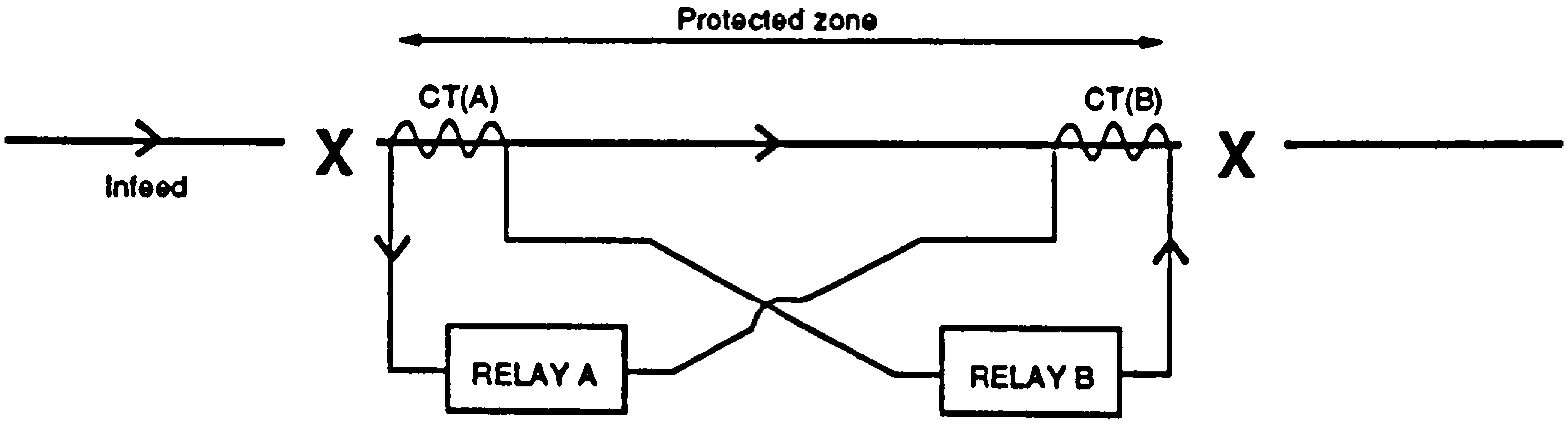


Figure 2.2: Balanced voltage unit protection scheme.

To define a current both magnitude and phase must be used. However, it is not always easy to send all this information over pilot channels. If only the magnitude of the terminal currents is used for comparison then adequate discrimination is not guaranteed. Nevertheless, the direction or phase of the currents is adequate for simple two-ended feeder arrangements. This comparison can be made directly, or by using a third common quantity as a reference. For direct comparison, the phase of each current is transmitted to the remote end over a suitable channel. Indirect comparison is possible using a third quantity, usually system voltage, as a link.

The technology used to provide the pilot channel will vary depending on the nature of the protection scheme. In certain circumstances, it is appropriate to rent circuits from a telecommunications company.

However, auxiliary wires are not always economical to use as pilots for interconnecting relays. Therefore, some other communications medium is used as a carrier to transfer information between two relaying points. These do not transmit power system frequencies, but modulate the signal appropriately. Possible media include voice-frequency channels, power line carrier, microwave links and optical fibres.

2.2.3.2 Non-unit protection schemes

Distance protection

Distance protection is a high speed class of protection which can provide both primary and backup functionality within a single scheme. Furthermore, it can be modified into a unit system by using a signalling channel.

Within this protection scheme the impedance between the protection relay and the fault is measured. However, as the impedance of a feeder is proportional to its length this is effectively a measure of distance. The current and voltage are measured at a relaying point, and from these the impedance to the fault is calculated. The relay operates if the impedance of the line up to the point of fault is greater than the predetermined reach point impedance. It is not considered to be a unit protection scheme in its own right since its zone of operation is not strictly defined. This can only be defined within the accuracy limits of the measurement. A schematic of the distance protection arrangement is shown in figure 2.3.

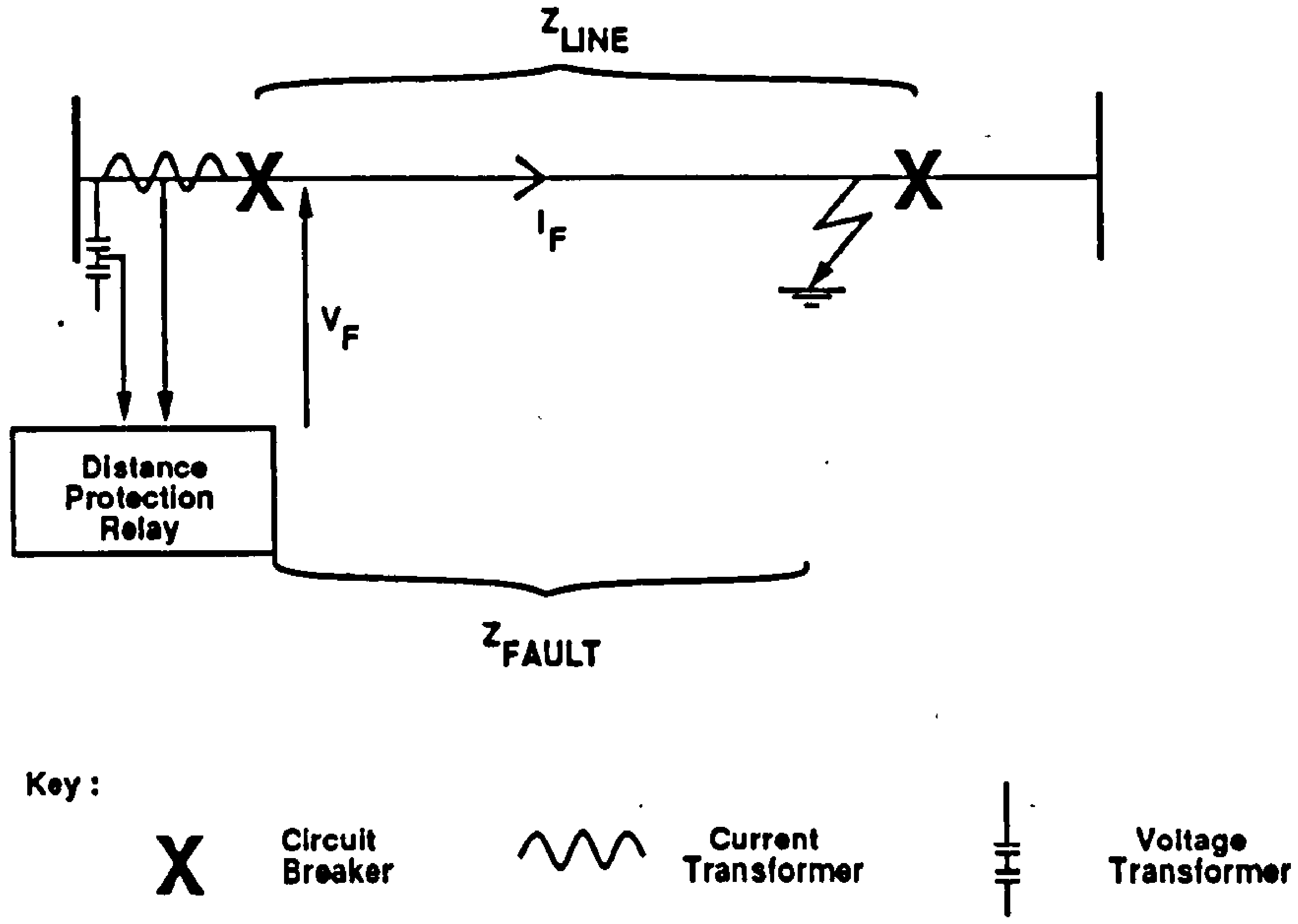


Figure 2.3: Distance protection scheme.

The reach settings and tripping times of zones of measurement are used to provide correct coordination between distance relays. Usually, distance protection will have an instantaneous directional Zone 1 protection and one or more time delayed zones. The standard practice is to select a Zone 1 setting of about 80% of the protected line, ensuring that Zone 1 does not over-reach. This is to prevent loss of discrimination with fast operating protection on the next line section due to errors in the current and voltage transformers, inaccuracies in line impedance data and errors of relay setting and measurement. Zone 2 is set to cover either the protected line plus 50% of the shortest adjacent line or 120% of the protected line, whichever is greater. Finally, Zone 3 has a forward reach of 1.2 × (protected line + longest second line), plus a reverse reach of 20% of the protected line. This provides time delayed local backup for busbar faults and close up three phase faults not cleared by other protections.

This coordination of distance schemes to offer backup protection, through zone overlap, can be seen in figure 2.4.

Since Zone 1 is configured to instantaneously clear faults up to 80% of the pro-

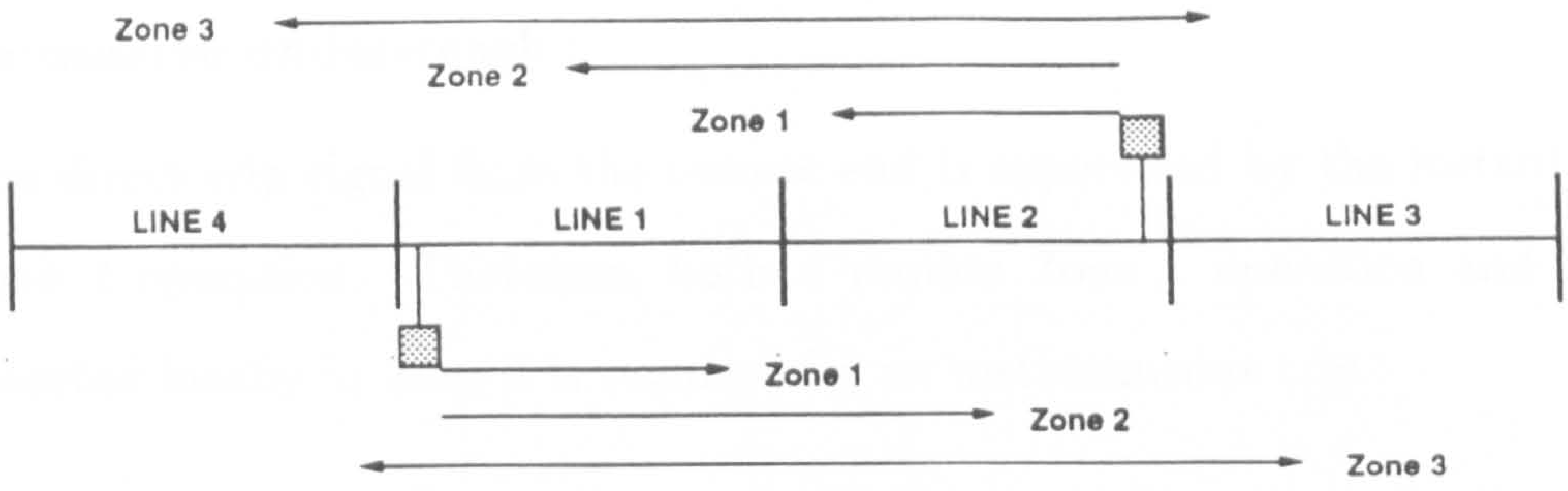


Figure 2.4: Zone overlap between distance protection schemes.

tected feeder, this means that for 20% of the feeder faults will be cleared instantaneously from one end and in Zone 2 time from the other end. This can affect system stability and the operation of high speed autoreclosing where applied (non simultaneous opening of the circuit breakers means that there is no dead-time during the autoreclose cycle for the fault to be extinguished).

A unit protection scheme would alleviate this problem, but does not provide backup protection cover to adjacent feeders. Therefore, the best course of action is to combine both types of protection. This can be achieved by interconnecting the distance protections at each end of the feeder via a signalling channel. This may be high frequency through overhead lines, voice frequency (pilots or power line carrier), radio link, microwave or a fibre optic link.

If this signalling channel initiates tripping of the remote circuit breaker then it is known as a transfer trip scheme. If the signal prevents tripping of the circuit breaker, it is a blocking scheme.

The following transfer trip schemes are used :

- **Intertrip** (direct transfer trip under-reaching scheme) :

  A Zone 1 contact sends a signal to the remote end trip relay which trips instantaneously.

- **Permissive under-reach :**

  The direct trip signal from the remote end is supervised by the instantaneous Zone 2 operation. Therefore, both a remote Zone 1 operation and a fault detected locally in Zone 2 is required for an instantaneous trip.

- **Acceleration :**

  This scheme is similar to permissive under-reach protection, but is only applicable to zone switched distance relays which share the same measuring units for Zone 1 and Zone 2. The reach of the measuring unit is extended from Zone 1 to Zone 2 after Zone 2 time.

  In this scheme the under-reaching Zone 1 relay sends a signal to the remote end. This immediately extends the reach from Zone 1 to Zone 2, accelerating fault clearance at the remote end.

Transfer trip schemes suffer when the signalling channel fails, or there is no infeed from one end. Under these circumstances end-of-zone faults will take longer to clear. To compensate for this, a blocking scheme can be used. Signalling is initiated only for external faults and signalling transmission takes place over healthy line sections. When no signal is received and a Zone 2 fault is detected, fast fault clearance occurs.

IDMT overcurrent protection scheme

Protection against excess current was the earliest protective system to be applied and developed. This has now become the graded overcurrent system.

To achieve correct relay coordination time, overcurrent or a combination of both can be applied. The common aim is to provide appropriate discrimination. That is, only the faulted section must be isolated, leaving the rest of the system undisturbed.

Discrimination by time alone has the disadvantage that the longest fault clearance time occurs for faults in the section closest to the power source, where the fault level is highest. Alternatively, discrimination by current can be applied only where there is an appreciable impedance between the two circuit breakers concerned. As a result of these problems, discrimination by time and current has evolved. IDMT protection is discussed as an example of overcurrent protection.

Inverse Definite Minimum Time (IDMT) overcurrent protection derives its name from the functionality it provides :

- The protection relay can be set to have a definite minimum operating time for a given fault current.
- The protection operation is based on an inverse characteristic i.e. $operating\ time \propto \frac{1}{I_{fault}}$.

Within this type of scheme the relays are current and time graded to provide the correct coordination. Assume IDMT protection is applied to a radial feeder as shown in figure 2.5.

When a fault occurs on a line, proper coordination means that the protection relay

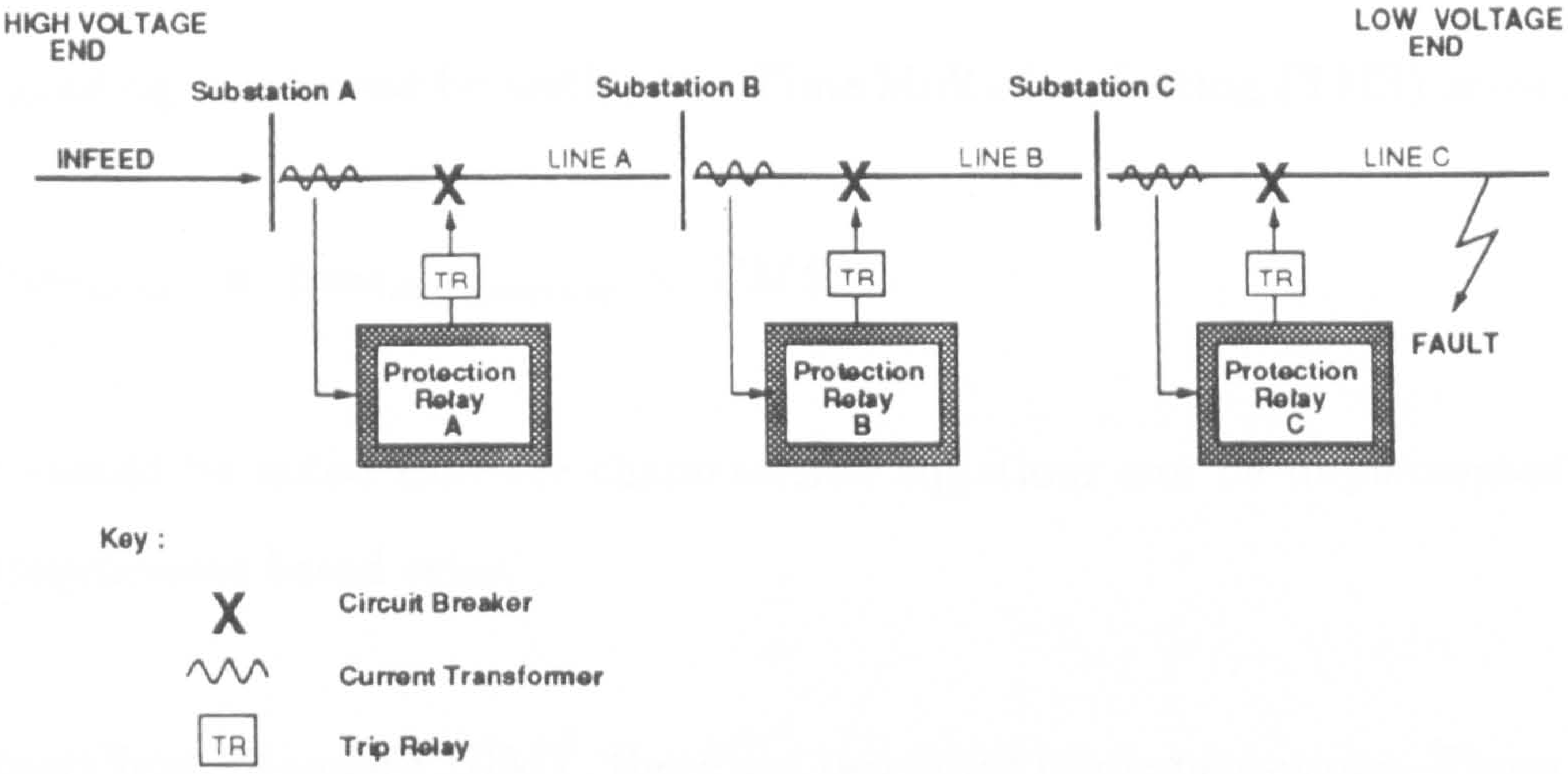


Figure 2.5: IDMT overcurrent protection applied to a radial feeder.

on that line will operate to clear the fault. If this fails to clear the fault (through maloperation of the protection relay, trip relay or circuit breaker) then backup is provided by the other graded relays (For example, in figure 2.5 protection relay A provides backup for faults on lines B and C). A set discrimination time is used to define the time of operation when a relay is providing backup cover.

Within an electromechanical IDMT overcurrent relay there are two settings which can be adjusted to permit the desired coordination to be achieved. These are the plug setting and the time multiplier setting. The operation of the IDMT protection relay can be defined in terms of characteristic equations based on these settings.

The Plug Setting Multiplier (PSM) is calculated in terms of the plug setting :

$$PSM = \frac{Primary\ fault\ current}{plug\ setting \times CT\ ratio \times relay\ rating}$$

For Standard IDMT (SIDMT) the characteristic equation which defines its operation is :

$$time_{characteristic} = \frac{0.14}{PSM^{0.02} - 1}$$

Time grading is achieved by setting the Time Multiplier Setting (TMS) accordingly :

$$time_{actual} = time_{characteristic} \times TMS$$

It should be noted that the characteristic equations can be implemented within a microprocessor based relay.

Apart from Standard IDMT, there are two other implementations. These are the Very IDMT (VIDMT) and Extremely IDMT (EIDMT) characteristics [14].

VIDMT is represented as follows :

$$time_{characteristic} = \frac{13.5}{(\frac{I}{I_s})-1}$$

where I is the fault current and I_s is the current setting.

EIDMT is characterised by the equation :

$$time_{characteristic} = \frac{80}{(\frac{I}{I_s})^2-1}$$

The difference between SIDMT, VIDMT and EIDMT is shown on the graph in figure 2.6.

2.2.4 Conclusion and bibliography

This section was intended to give an overview of the application domain, relevant to the research reported in this thesis, without being exhaustive. The basic concepts underpinning power systems and power system protection have been covered. For more detailed and comprehensive discussions and explanations of these areas, the reader is directed to the following reference material :

1. B.M. Weedy, *Electric Power Systems*, 3rd Edition Revised, John Wiley and Sons, 1987.
2. The Electricity Council (editor), *Power System Protection*, Volume 2, Macdonald and Co. (Publishers) Ltd, 1969.
3. S.H. Horowitz and A.G. Phadke, *Power System Relaying*, Research Studies Press Ltd and John Wiley and Sons, 1992.
4. *Protective Relays Application Guide*, 3rd Edition, GEC Measurements, 1987.

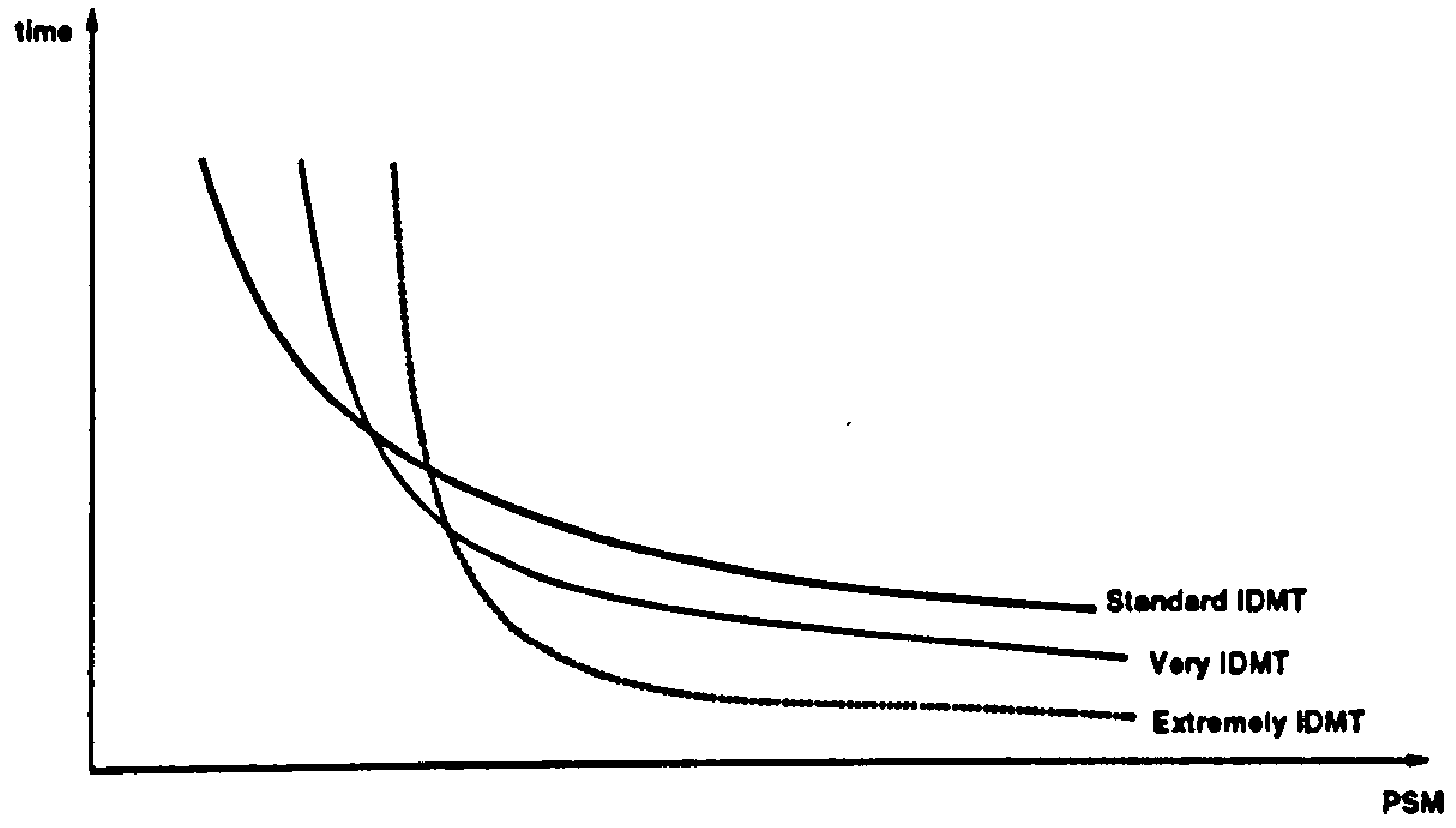


Figure 2.6: IDMT overcurrent protection characteristic curves.

2.3 Fundamentals of Expert Systems

2.3.1 Introduction to Artificial Intelligence

" It is not my aim to surprise or shock you....But the simplest way I can summarise is to say that there are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until - in a visible future - the range of problems they can handle will be coextensive with the range to which the human mind has been applied."

- Simon and Newell 1958.

The above quotation, in my view, summarises the idealists' concept of Artificial Intelligence (AI). However, it is difficult to provide a succinct and definitive description of what this field really is, which is a current research topic in itself [15]. In the engineering domain AI is seen as providing machines with the capability to perform specialised tasks which require some expertise, or human like intelligence. (Unfortunately, the terms "intelligence" and "machine" are open to interpretation [16], but it is not the intention of this thesis to debate the philosophical viewpoints of AI.) Within the realm of AI research a number of areas are explored. These are the theory, philosophy and application of AI. In terms of the research reported in this thesis, and indeed any engineering project involving AI, the work bridges the gap between theory and application, leading to the eventual development of an *intelligent system.*

A number of techniques, or paradigms, can be used to provide a machine (usually a computer) with "intelligence". This thesis is concerned with expert system technology, therefore the key paradigms in this area will be explained in the remainder of this section.

2.3.2 Expert Systems

An expert system emulates the reasoning of a human expert. Expert systems became an intensive research topic following the realisation that the goal of constructing an all purpose problem solving machine was too ambitious [15]. Therefore, very specific problems and domains, which required interpretation by a human expert, were targeted. The tasks of the expert are formalised and coded within an *expert system*. This offers a number of advantages :

- Human experts are scarce, therefore an expert system allows the dissemination of their expertise.
- Unfortunately, a human expert only has a limited working lifetime. Expert systems permit the retention of this expertise. By using modern knowledge engineering methodologies (e.g. KADS [17]) an archive of expertise can be produced. This facilitates the training of new personnel and the analysis of existing procedures.
- A number of the advantages of expert systems are specific to the application being considered. For example, in terms of the research being reported in this thesis, an expert system can interpret large data rates of alarms quicker than human experts. Such application specific advantages will be discussed when appropriate.

Within the realm of expert systems a variety of paradigms are employed. Each one differs in the format of knowledge storage/coding and the reasoning approach utilised. These can be split into three distinct categories :

- Knowledge Based System (KBS)

- Case Based Reasoning (CBR)
- Model Based Reasoning (MBR)

2.3.2.1 Knowledge Based Systems

A knowledge based system has some form of experiential knowledge coded within a *knowledge base*. This is used by the *inference engine* to perform some form of intelligent analysis/reasoning. Therefore, a KBS is inference driven as opposed to conventional software which is algorithm driven. This can be summarised as follows (derived from [18]) :

$$data + algorithm \longrightarrow conventional\ software$$

$$knowledge + inference \longrightarrow knowledge\ based\ system$$

Within a KBS, the knowledge base and inference engine should be independent to facilitate maintenance and updating of the knowledge. The key characteristic of a KBS is that human expertise is *compiled* within it, that is, constrained within some knowledge representation format appropriate to the inference mechanism.

The structure of a KBS is shown in figure 2.7. The heart of a KBS (shown with a shaded background in figure 2.7) comprises the knowledge base, data sources and inference engine. The data sources provide the KBS with the associated domain details required for the task which it is executing. For example, a fault diagnostic expert system may require data regarding the connectivity between devices. This is used, in conjunction with the knowledge base, when the inference engine is performing the reasoning process. A man machine interface is provided for the users of the KBS. Furthermore, there are designer utilities specifically for the knowledge engineers who build and update the KBS. An important issue for expert systems is their ability to justify, or explain, their conclusions and reasoning processes. The provision of facilities for the maintenance and updating of data and knowledge is equally important. An expert system with outdated knowledge or data is obsolete, and will not be used. Hence, the diagram shows the requirement for advanced functions within a KBS, which would encompass explanation and maintenance facilities.

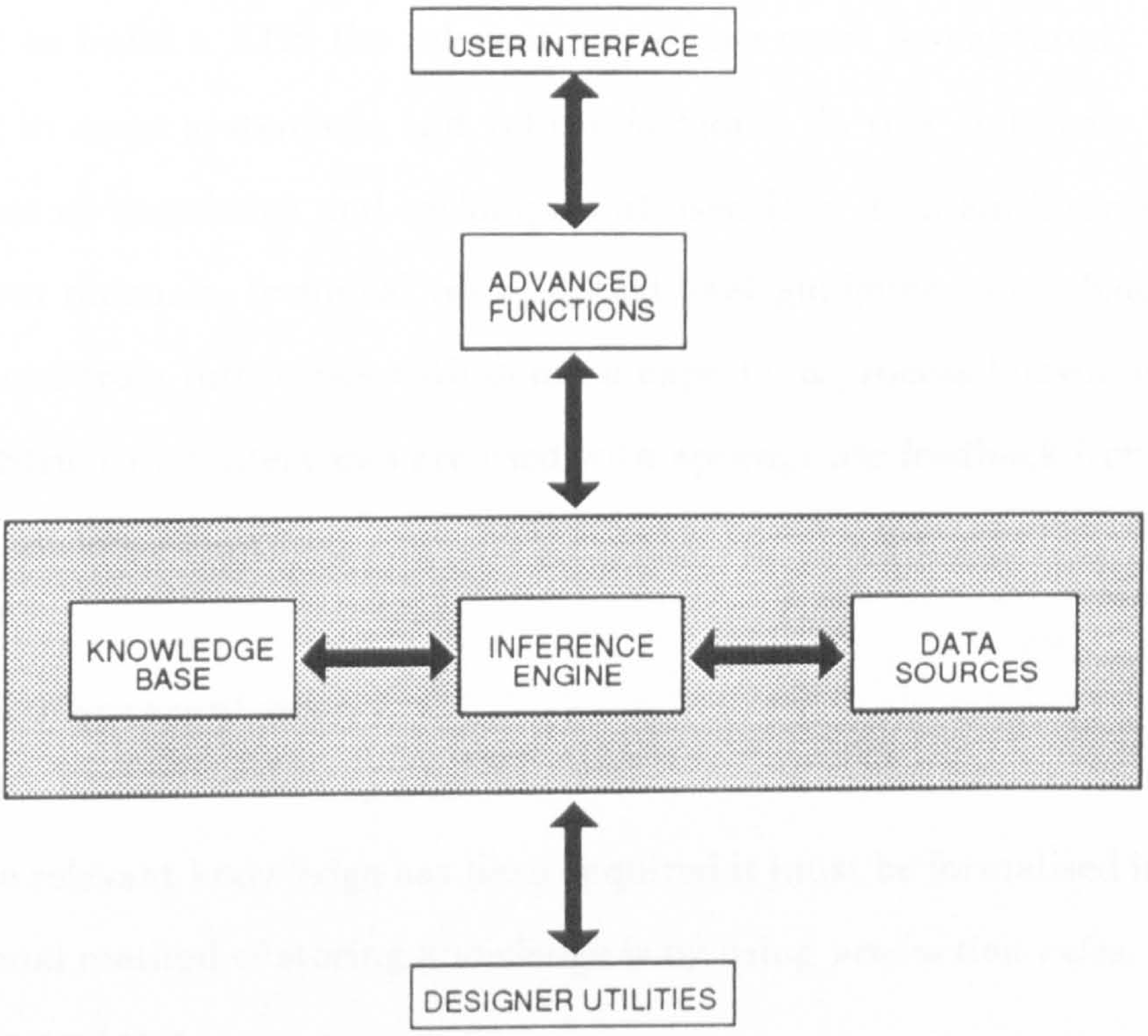


Figure 2.7: Knowledge based system structure.

When designing a KBS there are three important issues :

- **Knowledge acquisition**

  The knowledge for the KBS can come from human experts or other sources such as reference books.

- **Knowledge representation**

  The knowledge must be stored in some formalised way. Rules and causal networks are possible mechanisms to achieve this.

- **Inference mechanism**

  The inference engine must manipulate the knowledge in some fashion. For example, backward and forward chaining.

Knowledge Acquisition

In order to build a KBS the relevant knowledge must be captured. This has to be achieved in some systematic and robust fashion. To this end there are a number of sources of knowledge and techniques utilised [19]. Domain knowledge can be obtained from manuals, technical texts, operational guidelines, etc. Knowledge can also be gleaned from interviews with domain experts, a process known as *knowledge elicitation.* Structured interviews are used with appropriate feedback from the expert about the knowledge captured.

Knowledge Representation

Once the relevant knowledge has been acquired it must be formalised in some way. One traditional method of storing knowledge is by using *production rules.* These have the following syntax :

IF premise THEN consequence

An example of a diagnostic production rule would be :

IF the ignition is on AND the electrics do not work THEN the battery is flat

If the knowledge stored is some coded form of a rule-of-thumb, or some type of human interpretation of events (such as the diagnostic production rule above), then it is called a *heuristic.*

Another approach which can be taken is the use of a *causal network.* As an example, the CHECK (Combining HEuristic and and Causal Knowledge) architecture [20] uses heuristics to perform an initial diagnosis and then a detailed causal network to further refine and validate the original conclusion. CHECK employs different nodes within its causal network to represent the following: hypotheses; states; actions; initial causes; findings. This is demonstrated in figure 2.8 showing a causal network in the domain of car troubleshooting [20]. In this diagram double lined ellipses indicate initial causes, rectangular boxes represent actions, single lined ellipses show states and rhomboidal boxes are findings.

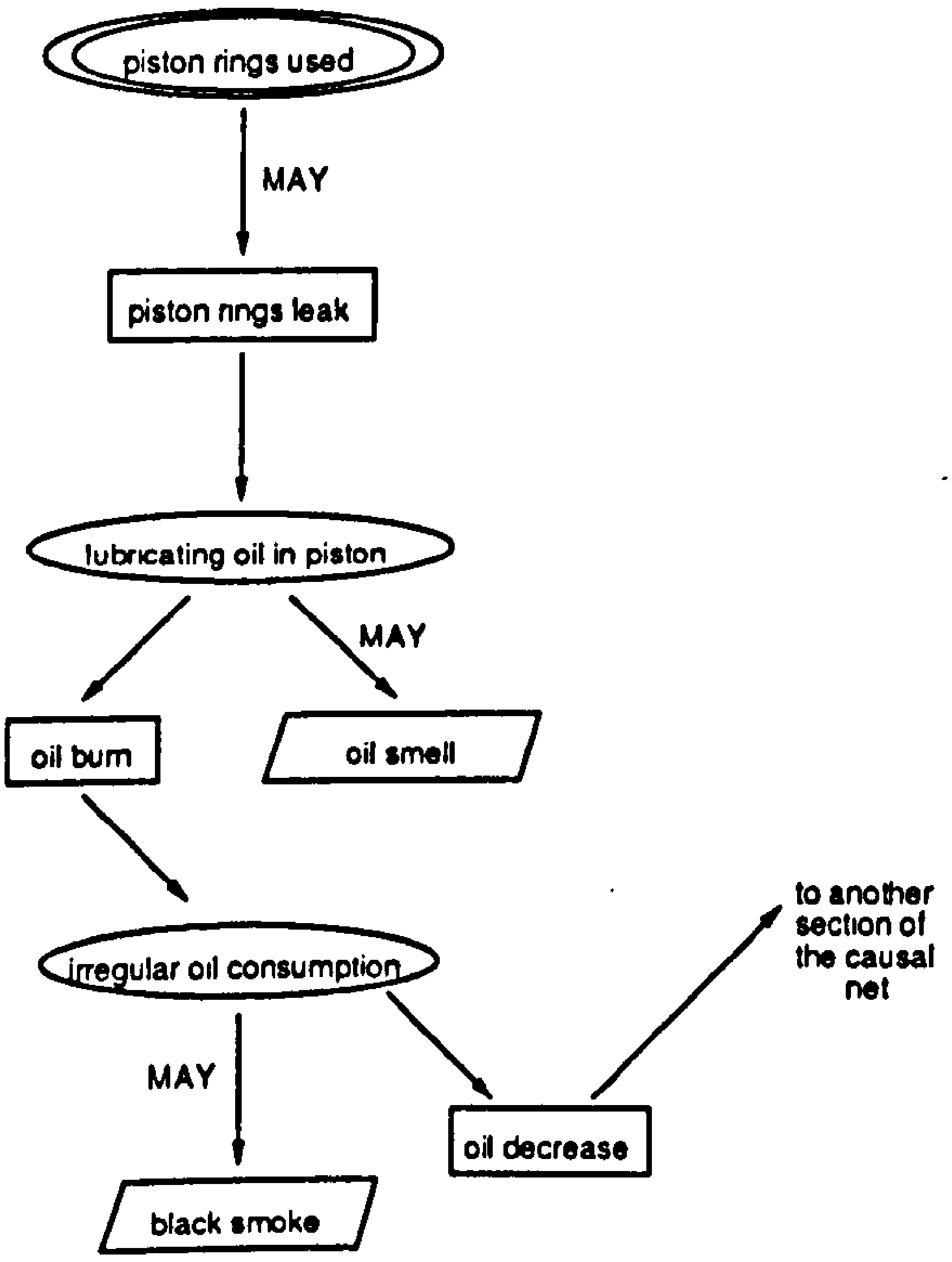


Figure 2.8: An example of a causal network.

Inference Mechanism

Given that knowledge has been encoded in some form, the inference engine must be able to navigate the search space. That is, it must be able to reason with the given knowledge. If we take the example of a production rule :

IF *a* THEN *b*

it can be seen that there are two possible ways of using this rule. Given *a*, *b* can be inferred. Alternatively, given *b* then *a* can be assumed. As a result two search mechanisms are possible :*forward chaining* and *backward chaining.*

Forward chaining is the progression from facts to goals (i.e. from *a* one can deduce *b*), and can be termed as data-driven. Backward chaining takes a goal and derives the expected facts or evidence which would support it (i.e. given *b*, *a* would be expected). This can be compared with the known facts. Backward chaining is also known as goal-directed reasoning.

When considering the forward and backward chaining approach to reasoning there are two control strategies which can be adopted. These are *depth-first search* and *breadth-first search.*

In a depth-first search all the successors within a single path are explored to their conclusion. This is repeated for each possible path until the desired conclusion state is reached. A breadth-first search explores all the subnodes of the present node before moving to the next level down, and continues to examine layers of the search space until the desired goal is achieved. Both methods are shown in figure 2.9.

By way of comparison, a breadth-first search will find the optimal path to a conclusion, if one exists, whereas a depth-first approach will be quicker providing it is guided in some way. Graph navigation techniques can also be used for a causal network based KBS.

More recently, structured knowledge analysis techniques have been used to gen-

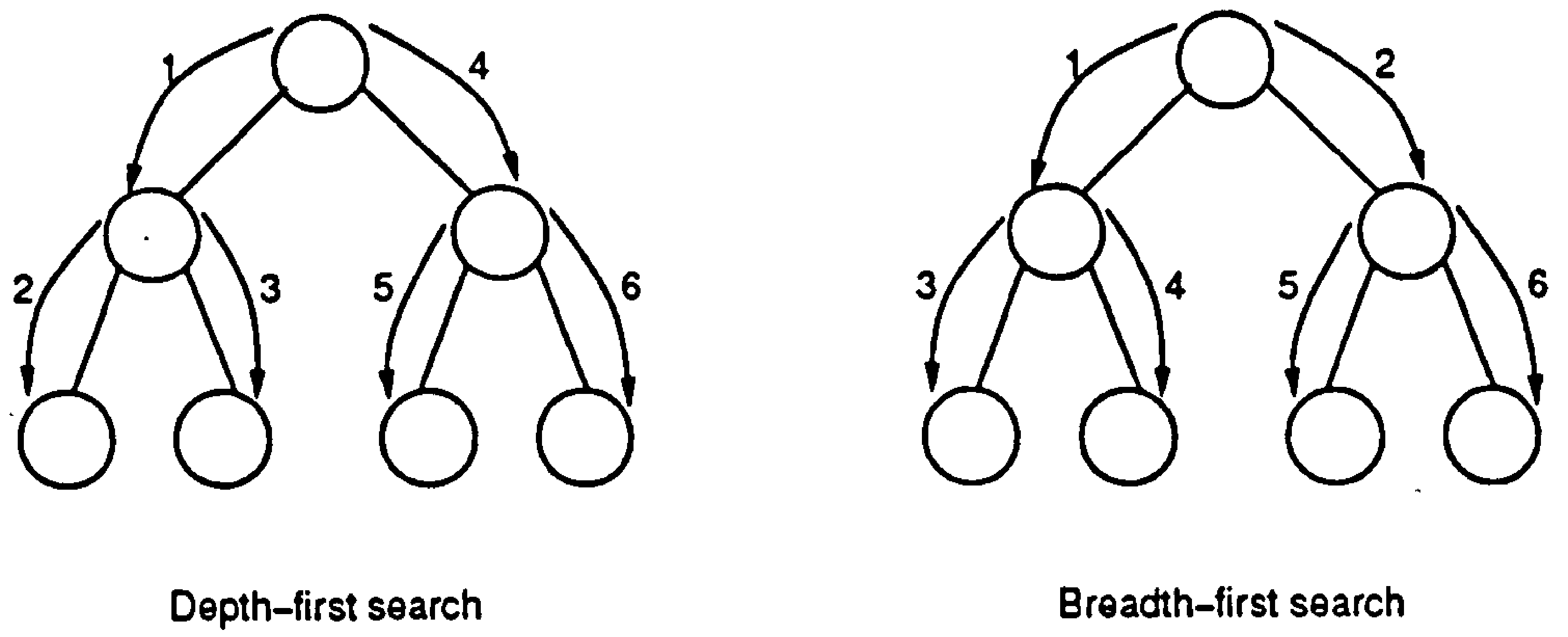


Figure 2.9: Search strategies.

erate knowledge based systems, such as the KADS methodology [17]. KADS uses a three-tier knowledge model which comprises task models, inference models and domain models. In addition to the benefits of a structured approach to KBS design, KADS offers an archive of the knowledge within the KBS which in itself can be useful for training or strategy assessment purposes [21].

2.3.2.2 Case Based Reasoning

"Case based reasoning is a method of solving a current problem by studying the solutions to previous, similar problems" [22]. The reasoning process used within CBR is shown in figure 2.10. A *case* can be defined as a scenario description along with the relevant actions taken to respond to it. These are stored in a *case base.* Given that the case base is updated following every problem analysed, CBR can be viewed as a *learning* methodology.

There are a number of advantages associated with the CBR paradigm :

- The mechanism employed is closer to the actual human decision process.
- The incorporation of new knowledge within the case base is automated.

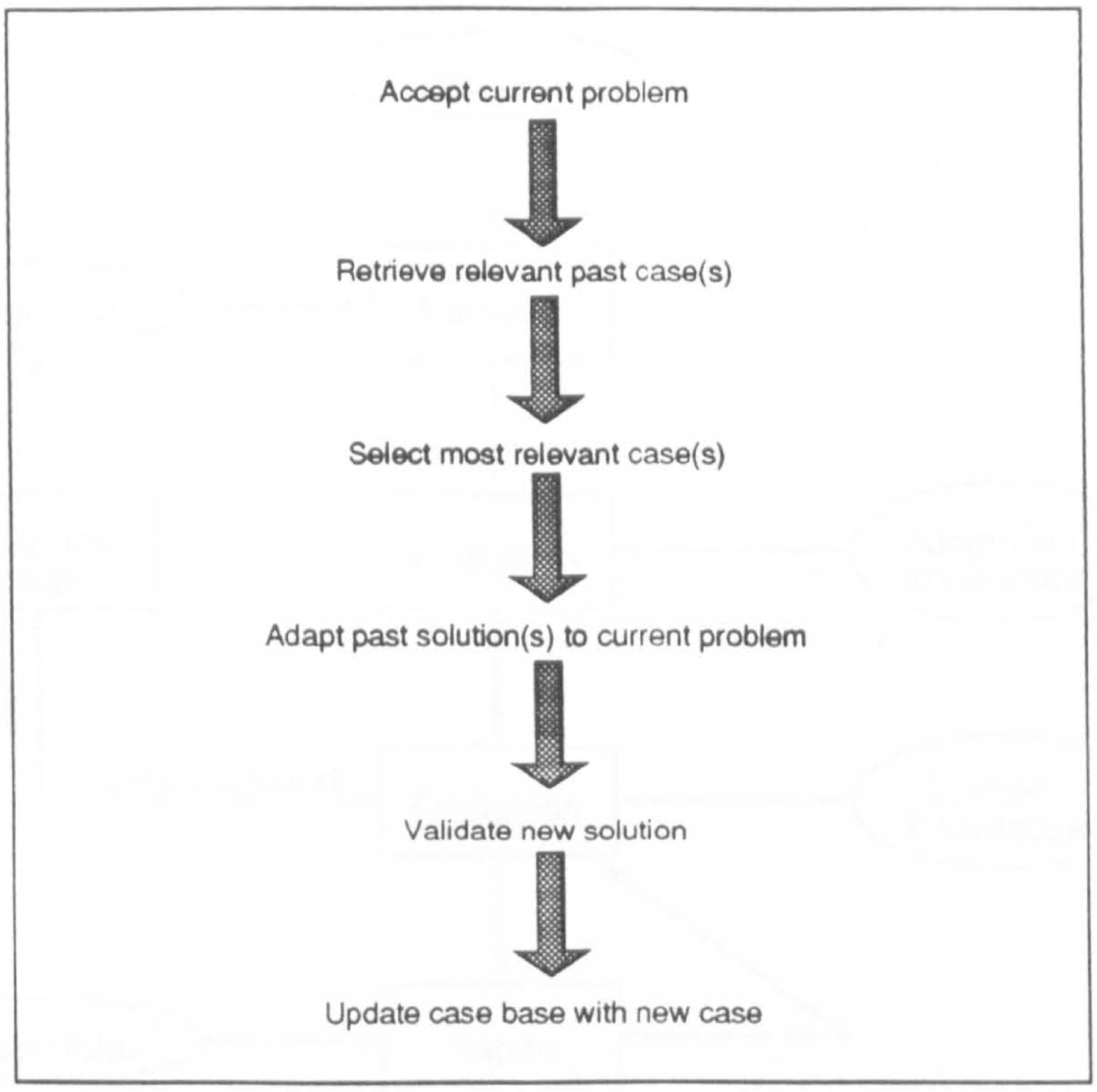


Figure 2.10: Case based reasoning process.

- Improved explanation and justification capabilities are possible, through showing the examples which supported the reasoning.
- CBR can be used in poorly understood domains, where experience rather than theory is the primary source of knowledge.

An example CBR system structure is shown in figure 2.11, taken from [23].

There are a number of key issues associated with a case based approach to reasoning [22] [24] :

- **Knowledge representation.**

  An appropriate and consistent vocabulary is necessary for the CBR system, its users and designers.

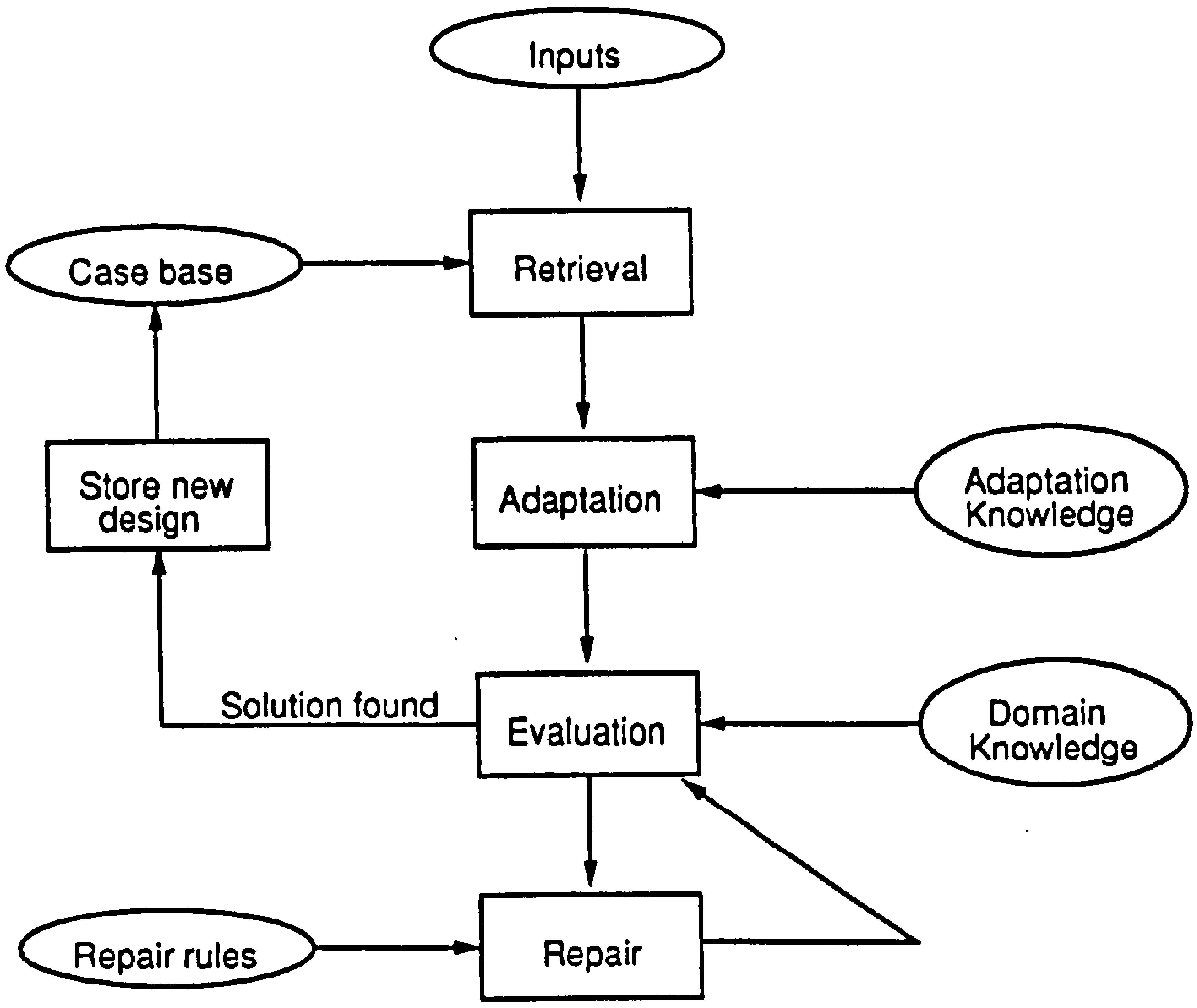


Figure 2.11: An example CBR system structure.

- **Cluster analysis.**

  Computer storage is a limited resource. Therefore, a clustering approach needs to be taken for similar cases, with redundant cases being eliminated.

- **Case storage and retrieval algorithms.**

  With the accumulation of cases the retrieval process becomes time consuming, and the storage process more complicated. Therefore, appropriate storage and retrieval algorithms are essential.

- **Case adaptation.**

  A closely matching case must be transformed into a complete match. User input or integrated rules can be used to perform this task.

Although closely aligned with KBS approaches, CBR takes experiential knowledge and uses each case in its entirety for reasoning purposes. A KBS approach would partition each case into defined blocks of useful knowledge, and from these the required minimal knowledge for implementation would be derived.

2.3.2.3 Model Based Reasoning

When using a knowledge based or case based paradigm the essence of the reasoning and knowledge modelling approaches are based upon human experts' experience within a domain. However, if detailed models representing the functionality of a device/system can be derived, this level of understanding can be capitalised upon within the reasoning process. Indeed, an accurate model can lead to reasoning from first principles understanding of functionality (e.g. physics laws/relationships). This represents a shift from rules, heuristics and case studies which tend to associate cause and effect empirically, but not through any strongly defined relationship. Model based reasoning is the use of detailed device/system models for reasoning purposes.

This approach to reasoning permits a variety of entities to be modelled [25], such as an object, device or system. Alternatively, a complete domain could be modelled (e.g. Physics). The choice of entity depends on the specific application. For example, if the objective is to diagnose faults in the electrical power system then we can model the power system in terms of the components within it. These include feeders, protection devices and plant. Models representing their behaviour with respect to voltage and current could be created, including their interaction with one another. However, if the task was to validate the design of a new circuit breaker then a model encompassing electrical, physical and mechanical aspects of its operation may need to be used.

Once the modelled entity has been selected, a further choice on model characteristics must be made [25] :

- Modelling approach : Qualitative, Quantitative, ...
- Modelling 'Language' : Equational, Logic, ...
- Modelled Aspect : Structure, Function, Causal mechanisms.

Obviously, the choice of model characteristics is dependent on the requirements of the model based system. For example, models of structure, behaviour and function can be utilised for diagnostic reasoning. As their title suggests, these models characterise a systems structure, behaviour and function. The structure defines the interaction of independent devices within the system. Each device has its behaviour modelled i.e. the translation from inputs to outputs. Through models of the device behaviours and interconnections the actual overall function of the system has been characterised. Consider the classic multiplier-adder circuit [10] shown in figure 2.12.

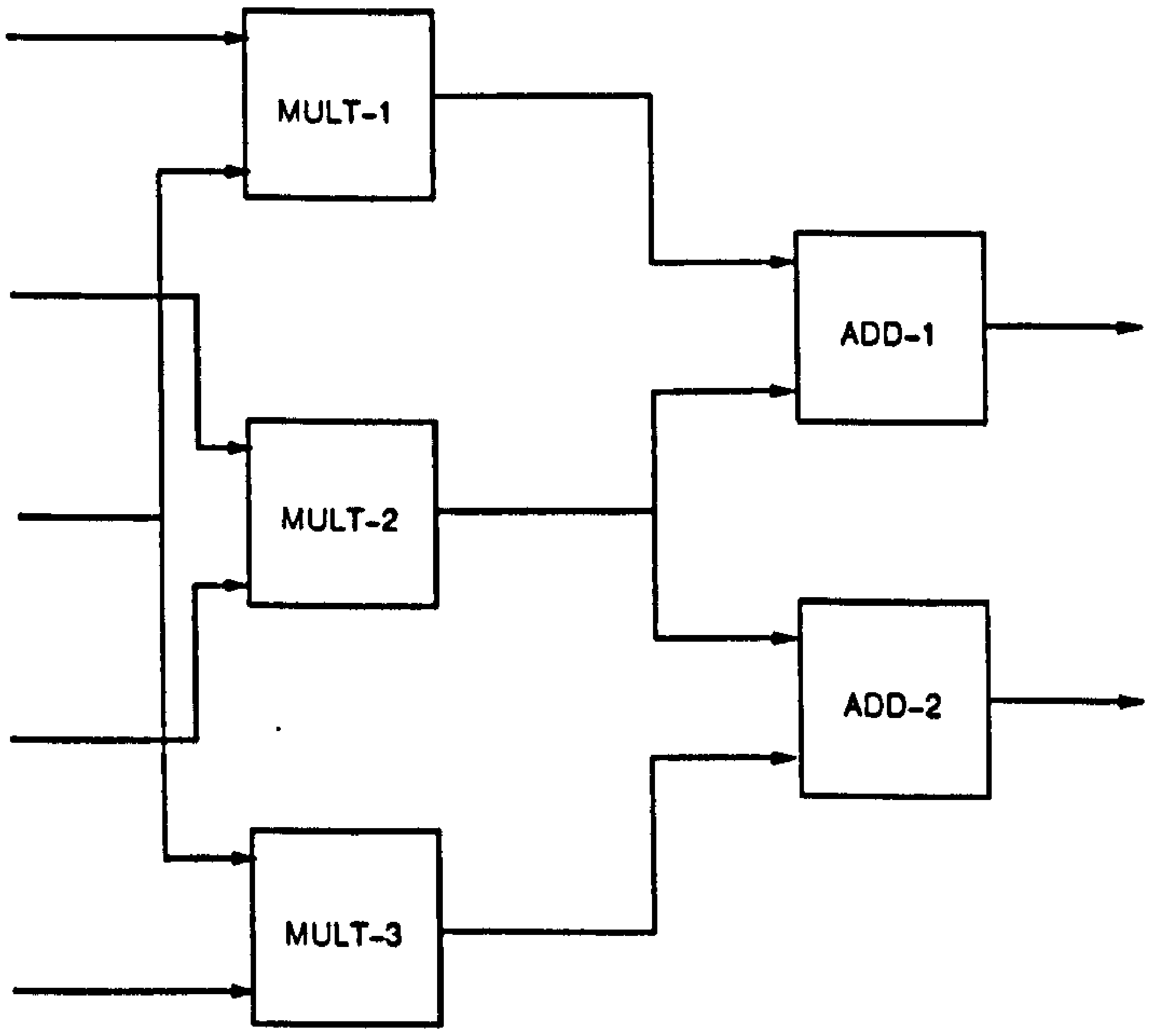


Figure 2.12: Model of a multiplier and adder circuit.

The behaviours of the two devices can be modelled as :

$$\text{ADD-X} = \text{INPUT1} + \text{INPUT2}$$
$$\text{MULT-X} = \text{INPUT1} \times \text{INPUT2}$$

Obviously, the behaviour models are not constrained to any particular type, therefore logic based, equational or composite models can be employed depending on the requirements of the MBR system.

MBR is often used for diagnostic purposes whereby the models predict expected behaviour of a device or system. This is compared with the actual behaviour of the device or system under study. The model is then exploited to explain any discrepancies encountered between expected and actual operation [10].

Benefits of model based reasoning

There are a number of benefits to be gained by adopting a model based reasoning paradigm:

- **Reasoning about novel events.**

  A detailed functional model will allow reasoning to take place on novel events (i.e. those not already encountered), due to the depth of understanding of the system under consideration. This differs from knowledge based techniques which only react correctly to events for which they have pertinent compiled knowledge.

- **Reasoning about complex scenarios.**

  With the greater detail of model used within MBR, more complex scenarios can be catered for.

- **Graceful degradation.**

  The competence of the reasoning can be assessed since the quality of models used is known. That is, it is more obvious when MBR reaches the boundary of its capabilities.

- **Improved efficiency.**

  MBR can operate under instances of incomplete data sets, since the model itself may be able to compensate for this.

- **Multiple uses of the models.**

  Given that models of function are employed, these can be used for a variety of tasks, including :

  - Reasoning.
  - Explanation.
  - Simulation.

The key issue relevant to MBR (which was alluded to in the third point above) is the completeness of the models in use. The reasoning can only be as accurate as the models which have been provided.

2.3.3 Discussion and bibliography

Expert systems are applied widely to problems and tasks within the domain of power engineering [3] [4] [5]. These include : alarm processing; fault diagnosis; system restoration; security assessment; reactive power and voltage control; switching operation; load flow planning; transient stability problems; unit commitment; operator training; maintenance scheduling; substation automation; plant monitoring.

However, it is apparent that no single paradigm will solve all the problems, due to the differences in their strengths and capabilities. Therefore, present and future effort into this application of expert systems must concentrate on multi-paradigmed approaches to solving the problem at hand. Indeed, this approach is adopted within the decision support system described in this thesis.

This section has not covered expert systems exhaustively and the interested reader is directed to the following texts :

1. P. Jackson, *Introduction to Expert Systems*, 2nd Edition, Addison-Wesley Publishers Ltd., 1990.
2. J. Kelly, *Artificial Intelligence : A modern myth*, Ellis Horwood Ltd., 1993.
3. S. Russell and P. Norvig, *Artificial Intelligence : A modern approach*, Prentice Hall, 1995.
4. Giarratano et al., *Expert Systems: Principles and Programming*, PWS-KENT, 1989.
5. J. Kolodner, *Case-Based Reasoning*, Morgan Kaufmann Publishers, Inc., 1993.

2.4 Chapter Summary

This chapter introduced the fundamental technologies underlying the research being reported. The thesis describes an expert system application within the field of power systems, and specifically power system protection. A perspective was given on the fundamentals of these topics, with relevant reference material indicated.

Chapter 3

A Decision Support System for Protection Engineers

3.1 Chapter Overview

This chapter discusses the requirement for a decision support system to facilitate the data analysis tasks of protection engineers. The desired functionality of the DSS is described with reference to the role of protection engineers and the data analysis problems they encounter. In this way the required functions are identified as: alarm processing; fault diagnosis; comprehensive validation of protection performance. Having identified the tasks of the DSS, their implementation paradigms are discussed. A knowledge based module provides the alarm processing and fault diagnosis functions while model based reasoning is seen as the appropriate technique for comprehensive protection performance validation. The knowledge based module is discussed, covering the two intelligent systems which it comprises of, and a case study of its operation is given to highlight the form of data analysis being provided. Within the context of the research presented in this thesis the design and construction of the two intelligent systems are not strictly important. Instead, their application in the domain of SCADA system data interpretation for protection engineers is the issue. As such, details of their design are provided in Appendix A.

3.2 The Requirement for a DSS

The requirement for a decision support system, tailored for utility protection engineers, was covered to some extent in the Justification for Research (Chapter 1, section 1.2). Nevertheless, it is appropriate to discuss the relevant issues in greater detail.

3.2.1 The role of protection engineers

Protection engineers design, analyse and maintain the protection systems resident within power system plant and networks. Following any significant power system disturbance they must determine whether the protection schemes operated correctly or not. This includes determination of whether a genuine fault occurred on the line, busbar, plant, etc. Their initial investigations are performed on the relevant SCADA system data, an example of which is given below :

```
07:08:14.85   HUER4   INKI   FIRST MAIN PROT OPTD         ON
07:08:14.85   HUER4   INKI   TRIP RELAYS TO BE RESET-E    ON
07:08:14.88   HUER4   X105   OPEN CLOSED                  OPEN
07:08:14.91   HUER4   INKI   AUTO SWITCHING IN PROG       ON
07:08:14.71   DEVM4   INKI   FIRST MAIN PROT OPTD         ON
07:08:14.71   DEVM4   INKI   TRIP RELAYS TO BE RESET-E    ON
07:08:14.74   DEVM4   X120   OPEN CLOSED                  OPEN
07:08:14.76   DEVM4   INKI   SECOND MAIN PROT OPTD        ON
```

Table 3.1

Through knowledge elicitation meetings with protection specialists it was gleaned that their initial interest is in the "significant" events (as subjectively defined by the engineers) taking place, as determined by interpretation of SCADA system data. For example :

- Protection activity.
- Isolation of plant due to switchgear movements.
- Autoswitching sequences.
- Reconnection of disconnected plant.

Such events are indicated by *primary* SCADA system alarms, which are associated with protection activity and primary plant movement. However, the protection engineers are also interested in *secondary alarms*, indicating circumstances which result in a depletion of protection operation, such as pilot wire problems for unit protection schemes and trip supply failures. The third class of SCADA system alarms are general events which require site intervention to solve. For example, battery earth faults at substations.

Once the key events have been determined an overall scenario description is the next goal. As an example, consider the case where two main protections are resident at each end of a feeder within a transmission system (this is usually the case at the 275kV and 400kV voltage levels). If the SCADA system data indicated the following :

- two main protections had operated at each end of the circuit
- the relevant circuit breakers had opened
- autoswitching had taken place
- the appropriate circuit breakers had reclosed

then the ensuing conclusion would be that a *temporary* fault had been switched out and the circuit had been successfully reclosed afterwards. If after reclosure the protection reoperated immediately, once more switching out the circuit, then a fault obviously still exists on the feeder, leading to the conclusion that a *permanent* fault is being experienced.

If only one main protection (out of the possible two) at either end of the circuit was indicated as having operated then the health of both protection relays is called into question. The operation and non-operation must be validated. Interestingly, a protection philosophy is that "if protection operates, you have a primary power system fault until proven otherwise". Unfortunately, SCADA system data does not indicate if a protection relay functioned correctly or not. Thus, the data captured by fault recorders (or modern protection relays with inbuilt data recording facilities) is utilised to perform a detailed analysis and validation of protection performance. This is not only to find possible protection maloperations but also to determine whether the fault was cleared within the correct timescale.

Fault records indicate the three phase voltages and currents experienced before, during and after a power system disturbance. Furthermore, the timing of protection relay operations, intertrip signals, trip relay activity, circuit breaker activity and other relevant device operations is captured. An example of the type of analogue data traces produced by a fault recorder are shown in figure 3.1. These show the current and voltage experienced during a blue phase to earth fault.

Fault records are used to validate the protection scheme operations, and to determine the nature of the power system fault experienced (i.e. single phase to earth, phase to phase, etc.).

3.2.2 Problems experienced by protection engineers

At the outset of this research the lack of an extensive corporate telecommunications network within the utility dictated that the protection engineers would receive SCADA system data in paper format from the grid control centre. Unfortunately, this could incur up to a number of days delay between a disturbance and the protection engineers' receipt of the relevant SCADA system data. This delayed the required protection performance analysis.

Coupled with this data availability problem the amount of SCADA system data

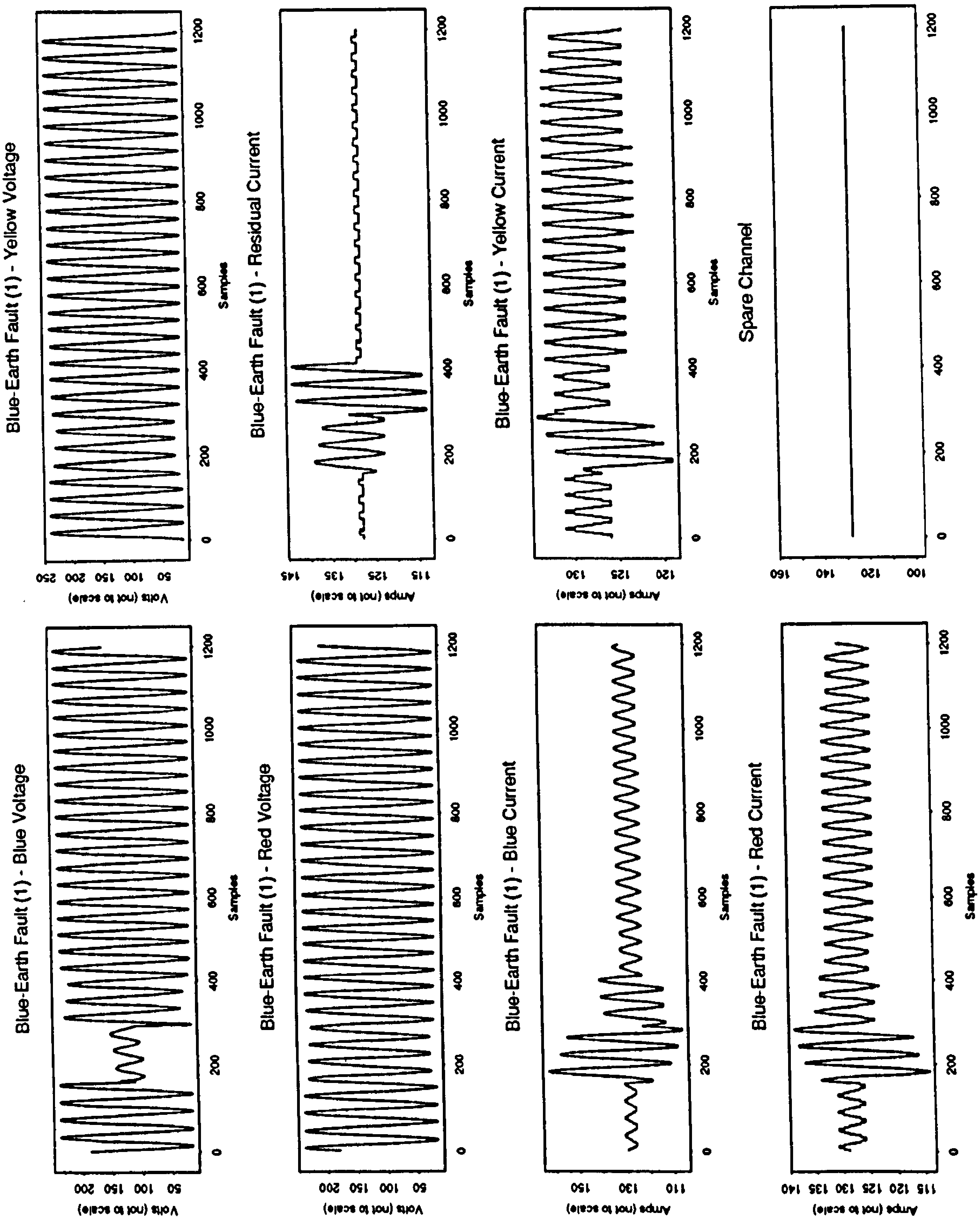


Figure 3.1: Analogue fault record data for a blue phase to earth fault.

to be processed can be overwhelming following any major disturbance. By way of an example, one disturbance generated three hundred alarms over fifteen minutes. For the protection engineers the important information taken from this data was that two faults had occurred, in quick succession, on a transmission line. The amount of alarms to be interpreted increases rapidly when a number of power system faults occur on the network (e.g. as a result of a storm).

The interpretation of this SCADA system data should point to relevant fault records to be retrieved and analysed, which again adds to the burden of the protection engineers. The situation is exacerbated by the fact that, generally, electric utilities are undergoing structural changes. This will lead to a decrease in the availability of protection specialists and a reduction in the time available for the engineers to devote to protection performance analysis, given their changing roles and responsibilities.

3.2.3 Solutions to the problems experienced by protection engineers

Essentially, two main problems need to be addressed :

1. The availability of SCADA system data.
2. The interpretation of SCADA system data and fault records (from fault recorders or modern microprocessor based protection relays) to validate protection performance.

The first issue was solved by implementing an extended telecommunications network which provides on-line SCADA system data to the protection group at the utility's corporate headquarters. As described in the Justification for Research (Chapter 1, section 1.2), three distribution control centres are used as data concentrators which forward the SCADA system messages via X.25 communication links. Within the protection group's computing facility the SCADA system data is archived in a microVAX based relational database. A local area network (LAN) allows multiple points of access to this data. Furthermore, fault records can be retrieved via computer based dial-up facilities. The network, as commissioned by the utility, is shown in figure 3.2

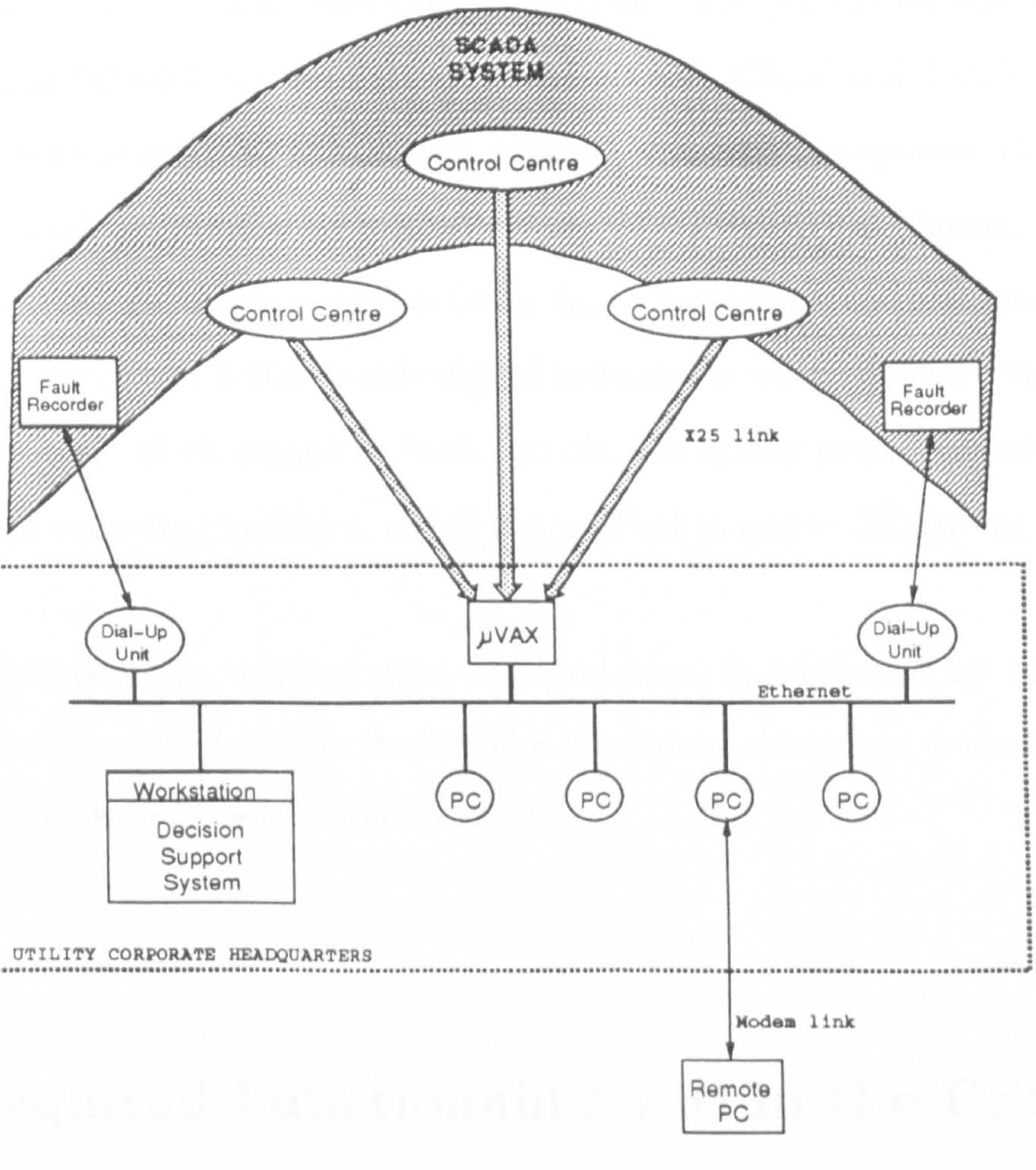


Figure 3.2: Extended telecommunications network providing on-line SCADA system data.

This extended telecommunications network and database archive of SCADA system messages offers a number of benefits :

- Access to on-line and historical SCADA system data.

- Improved browsing and searching of SCADA system data using database interrogation software.
- Off-site access to data through remote login to the LAN.

As a result of the telecommunications backbone the protection engineers were provided on-line SCADA system data from the 400kV, 275kV and 132kV networks, covering 126 substations. This has been extended now to incorporate alarms from the 33kV network amounting to a possible 18,000 single digital alarms, indicating protection system and other device activity (e.g. protection alarms, intertripping, autoswitching, etc.), and 5,000 double digital indications which describe any changes in switchgear state. With regard to fault records, the utility presently has 80 circuit ends with fault recording facilities, which is predicted to rise to 200 by the year 2000.

The second problem, that of data interpretation, is addressed by the decision support system described in this thesis. The fundamental concept underpinning the DSS is the extraction of *information* from *data.*

3.3 Required Functionality within the DSS

Studies have been carried out by IEEE Working Group D10 (concerned with applications of expert systems to power system protection) and by Cigré Working Group WG 34-07 (substation control and protection equipment design) into the potential utilisation of intelligent systems for protection applications [26] [27]. A number of applications have been suggested, such as :

- Protection selection, setting and coordination.

- Fault identification and location.
- Analysis of sequence of event recorders at the substation level.
- Analysis of digital fault recorder data.

As of yet these investigations have not indicated any work concerning an integrated intelligent system to interpret the varied data to be analysed by protection engineers. The research presented in this thesis identifies the need for a DSS as a data analysis tool for protection engineers, interpreting SCADA system data and fault records to produce a comprehensive study of any power system disturbance in terms of protection performance.

Following the discussions on the data interpretation tasks of protection engineers (Chapter 3, section 3.2.1), three key aspects can be extracted :

1. The determination of discrete events (such as protection activity, isolation of plant and feeders due to circuit breaker movement, autoswitching, etc.) based on the SCADA system data.
2. The production of a disturbance overview in terms of the type of fault which was being experienced, such as a permanent phase/earth fault on a transmission line. Once more this is based on the SCADA system data received. This activity can be seen as a diagnostic task.
3. The detailed analysis/validation of protection scheme performance using the data captured by fault recorders or equivalent devices.

These can be mapped onto separate functions (or tasks) to be performed by the DSS :

1. Alarm processing.

2. Fault diagnosis.

3. Comprehensive validation of protection performance.

Combining the outputs of these three tasks will provide a comprehensive study of protection operation.

The DSS has two main modules. The first of these is knowledge based in nature and performs the alarm processing and fault diagnosis tasks. The second module will utilise model based reasoning to validate the protection performance. The conceptual architecture is shown in figure 3.3. The next section of this thesis will deal with the knowledge based module of the DSS, while the model based validation of protection operations, its integration into the DSS and the ensuing data and information flow will be dealt with in later chapters.

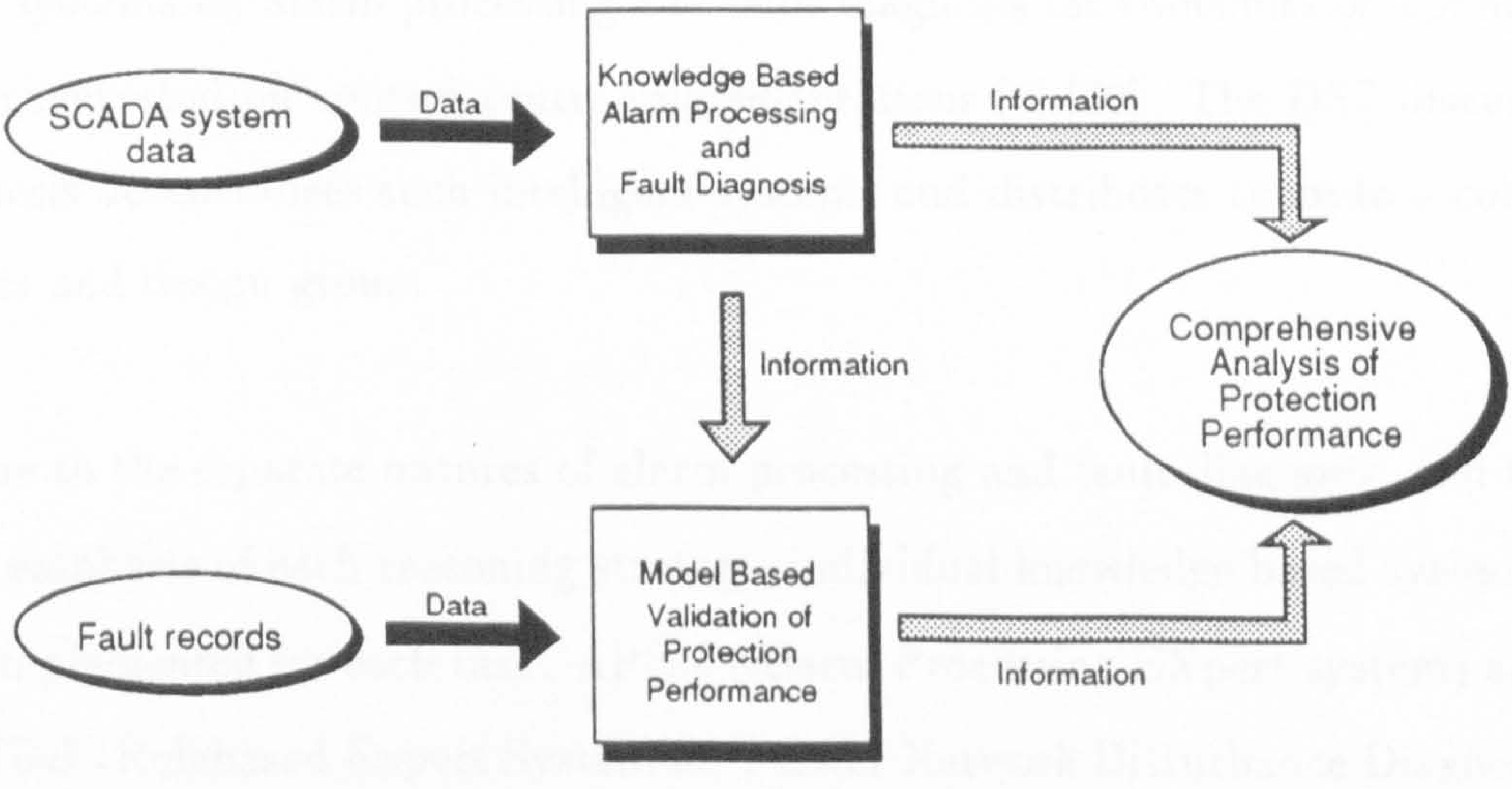


Figure 3.3: Conceptual architecture of DSS.

3.4 Knowledge Based Module of the DSS

3.4.1 Discussion

The knowledge based module performs alarm processing and fault diagnostic functions. A number of on-line decision support systems implemented for power system network applications view alarm processing and fault diagnosis as being synonymous [5] [28] [29]. Such a viewpoint is not supported in this thesis. *Alarm processing* is the identification of power system events (blackout areas, successful protection operations, etc.) from the incoming SCADA system data stream, and can be viewed as answering the question 'What is happening?'. *Fault diagnosis* is the derivation of the causal roots (phase/earth faults on feeders, failed protection, etc.) of the events deduced by the alarm processor. As such, this is a more detailed analysis, answering the question 'Why did the events occur?'. Research concerning the use of expert systems for alarm processing and fault diagnosis for transmission applications has concentrated on control centre implementations [4] [30]. The DSS discussed in this thesis decentralises such intelligent systems and distributes them to a corporate analysis and design group.

Due to the separate natures of alarm processing and fault diagnosis, and the different emphasis of each reasoning strategy, individual knowledge based systems have been implemented for each task. APEX (Alarm Processing EXpert system) and RESPONDD (Rulebased Expert System for POwer Network Disturbance Diagnosis) are the two knowledge based systems of the DSS which process on-line SCADA system messages. Both of these intelligent systems are the result of extensive previous research [7] [8] [31]. They were designed for control room implementation and through the course of this research they have been tailored to the data interpretation needs of protection engineers.

Both of these knowledge based systems adopt an hypothesising strategy. That is, they dynamically build hypotheses as more data becomes available. This can be termed incremental reasoning and differs from other approaches where a time window or snapshot of SCADA system data is captured before the reasoning begins [29] [32]. Such an approach allows them to compensate for missing or time skewed telemetry plus variable data arrival rates. Moreover, the hypothesising approach lends itself to reasoning about multiple and/or simultaneous events.

APEX is written in the 'C' programming language. This allowed an efficient inference engine to be built, which has been proven to process in excess of fourteen thousand alarms per minute [31]. The use of 'C' allows APEX to be platform independent, therefore portability is not a concern. The rulebase is in a near natural language format facilitating the creation of new rules by the protection engineers.

RESPONDD is written in the Prolog (*Pro*gramming in *log*ic) programming language [33]. Utilisation of Prolog was necessary to permit the detailed reasoning, required by this fault diagnosis expert system, to be implemented. RESPONDD's accuracy is derived from its qualitative simulator which simulates expected protection and plant activity for different fault types (phase/earth feeder faults, busbar faults, protection and plant maloperations, etc.).

A detailed description of the structure and operation of both APEX and RESPONDD is given in Appendix A. This describes how SCADA system data is interpreted and summarised by both of these knowledge based systems.

3.4.2 Case study of SCADA system data interpretation

This case study relates to a disturbance within the network shown in figure 3.4. The alarms received are shown overleaf from the diagram in table 3.2. As can be seen from the time tags the bulk of these were generated within twenty-six seconds with a final two alarms being declared four minutes later. In fact, the final two alarms relate to a second disturbance and clearly demonstrate how the SCADA system data to be analysed can quickly accumulate as more faults are experienced. The problem of time skewed data is obvious as they are not presented in chronological order. Furthermore, the alarms indicate events spanning three substations and two circuits which means multiple simultaneous faults are being experienced. Within the network in question there are autoreclosing facilities on the Rosebank to Kirkfield circuit, but none on the Rosebank to Crossford circuit. There are also intertrip facilities (which the local protection relay uses to automatically trip the protection at the remote end when a fault is detected) on the Rosebank to Kirkfield circuit, but none for Rosebank to Crossford.

From inspection of the alarm stream the key information is not apparent. Indeed, without knowledge of the power system topology and the implemented protection schemes then analysis of the alarms is difficult. However, the knowledge based module is able to extract pertinent information from the alarm stream.

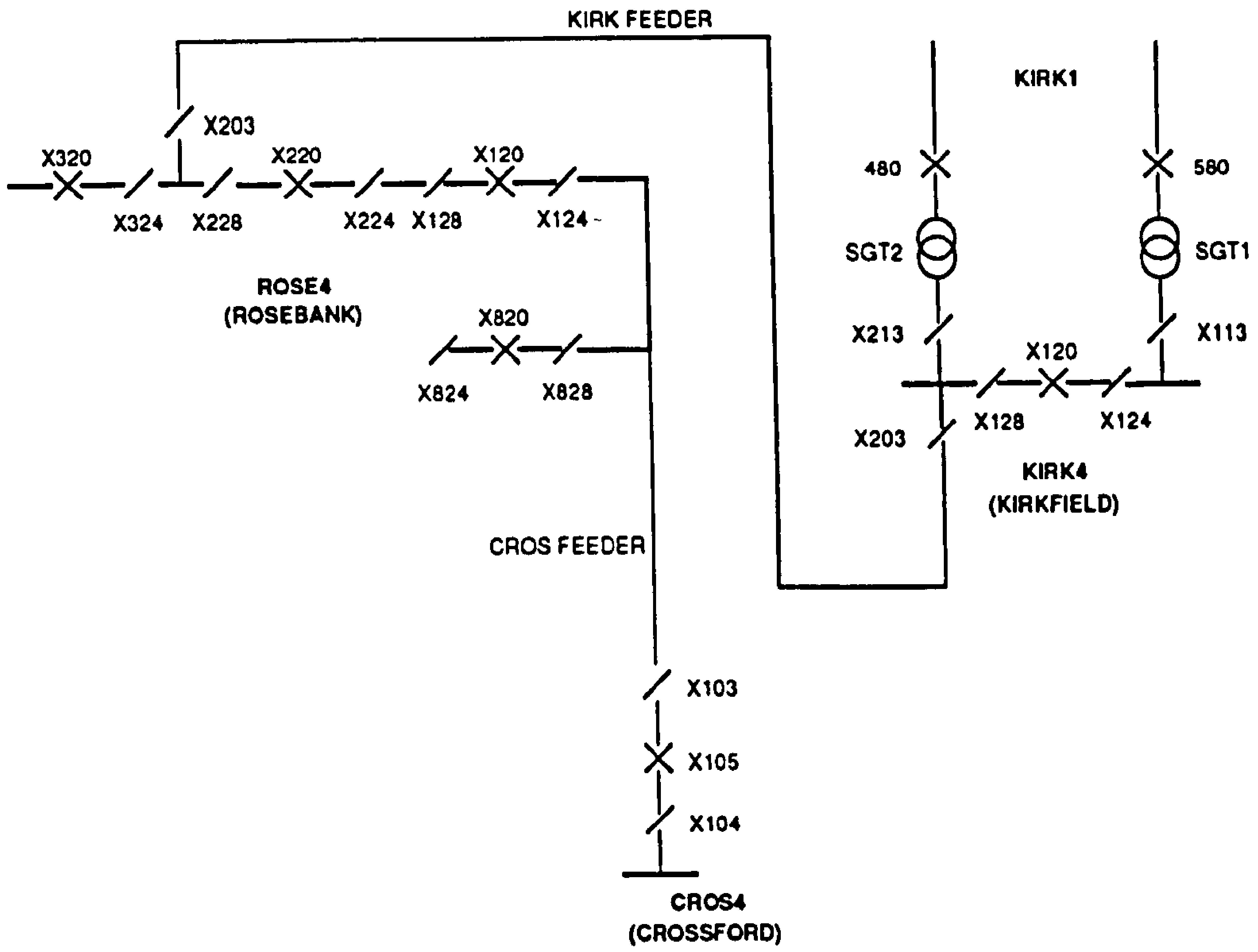


Figure 3.4: Power system network for case study.

13:08:14:85	CROS4	ROSE	FIRST MAIN PROT OPTD	ON
13:08:14.85	CROS4	ROSE	TRIP RELAYS TO BE RESET-E	ON
13:08:14.88	CROS4	X105	OPEN CLOSED	OPEN
13:08:14.71	KIRK4	ROSE	FIRST MAIN PROT OPTD	ON
13:08:14.71	KIRK4	ROSE	TRIP RELAYS TO BE RESET-E	ON
13:08:14.74	KIRK4	X120	OPEN CLOSED	OPEN
13:08:14.76	KIRK4	ROSE	SECOND MAIN PROT OPTD	ON
13:08:14.70	ROSE4	CROS	SECOND MAIN PROT OPTD	ON
13:08:14.71	ROSE4	CROS	TRIP RELAYS TO BE RESET-E	ON
13:08:14.71	ROSE4	KIRK	FIRST MAIN PROT OPTD	ON
13:08:14.72	ROSE4	KIRK	TRIP RELAYS TO BE RESET-E	ON
13:08:14.76	KIRK4	ROSE	FIRST INTERTRIP REC OPTD	ON
13:08:14.76	KIRK4	ROSE	SECOND INTERTRIP REC OPTD	ON
13:08:14.78	KIRK4	ROSE	AUTO SWITCHING IN PROG	ON
13:08:14.78	KIRK1	480	OPEN CLOSED	OPEN
13:08:14.73	ROSE4	X120	OPEN CLOSED	OPEN
13:08:14.74	ROSE4	X820	OPEN CLOSED	OPEN
13:08:14.74	ROSE4	CROS	FIRST MAIN PROT OPTD	ON
13:08:14.75	ROSE4	KIRK	SECOND MAIN PROT OPTD	ON
13:08:14.75	ROSE4	X220	OPEN CLOSED	OPEN
13:08:24.99	CROS4	ROSE	FIRST MAIN PROT OPTD	OFF
13:08:24.99	CROS4	ROSE	TRIP RELAYS TO BE RESET-E	OFF
13:08:14.84	KIRK4	ROSE	FIRST MAIN PROT OPTD	OFF
13:08:14.85	KIRK4	ROSE	SECOND MAIN PROT OPTD	OFF
13:08:14.75	ROSE4	X320	OPEN CLOSED	OPEN
13:08:14.76	ROSE4	KIRK	FIRST INTERTRIP REC OPTD	ON
13:08:14.76	ROSE4	KIRK	SECOND INTERTRIP REC OPTD	ON
13:08:25.58	KIRK4	ROSE	FIRST INTERTRIP REC OPTD	OFF
13:08:25.58	KIRK4	ROSE	SECOND INTERTRIP REC OPTD	OFF
13:08:14.78	ROSE4	CROS	SECOND MAIN PROT OPTD	OFF
13:08:14.79	ROSE4	KIRK	AUTO SWITCHING IN PROG	ON
13:08:25.58	KIRK4	ROSE	TRIP RELAYS TO BE RESET-E	OFF
13:08:35.87	ROSE4	X220	OPEN CLOSED	CLOSED
13:08:14.80	ROSE4	KIRK	SECOND MAIN PROT OPTD	OFF
13:08:14.80	ROSE4	CROS	FIRST MAIN PROT OPTD	OFF
13:08:14.86	ROSE4	KIRK	FIRST MAIN PROT OPTD	OFF
13:08:40.91	ROSE4	X320	OPEN CLOSED	CLOSED
13:08:35.86	KIRK4	X120	OPEN CLOSED	CLOSED
13:08:43.28	ROSE4	KIRK	AUTO SWITCHING IN PROG	OFF
13:08:24.66	ROSE4	CROS	TRIP RELAYS TO BE RESET-E	OFF
13:08:43.27	KIRK4	ROSE	AUTO SWITCHING IN PROG	OFF
13:08:43.29	KIRK4	ROSE	AUTO SWITCHING COMPLETE	ON
13:08:43.40	KIRK1	480	OPEN CLOSED	CLOSED
13:08:40.90	ROSE4	KIRK	AUTO SWITCHING COMPLETE	ON
13:08:25.80	ROSE4	KIRK	FIRST INTERTRIP REC OPTD	OFF
13:08:26.27	ROSE4	KIRK	SECOND INTERTRIP REC OPTD	OFF
13:08:43.41	KIRK4	ROSE	AUTO SWITCHING COMPLETE	OFF
13:08:26.32	ROSE4	KIRK	TRIP RELAYS TO BE RESET-E	OFF
13:08:40.92	ROSE4	KIRK	AUTO SWITCHING COMPLETE	OFF
13:12:40.60	KIRK4	ROSE	FIRST MAIN PROT OPTD	ON
13:12:40.61	KIRK4	ROSE	TRIP RELAYS TO BE RESET-E	ON

Table 3.2

Having presented the SCADA system data to APEX, the event summaries overleaf were generated. The necessary topological and SCADA system details were included in APEX's databases and the rulebase used is given in Appendix B. The rulebase, in the context of this case study, indicates for each summary the alarms which cause it to be generated.

The event summaries (shown in table 3.3) extract information of relevance to the protection engineers. These are indexed within this case study for clarity of explanation. They are not chronologically ordered as a result of the time skewed alarms and the nature of the alarm processor's operation. APEX outputs a hypothesis as soon as it is able to and labels it with the time of its initiating alarm.

Summaries 1, 4 and 10 are produced from circuit breaker activity, and indicate the area of the network which has been switched out or reclosed.

Summary 4 indicates that the Rosebank to Kirkfield feeder has been isolated along with transformer SGT2 at Kirkfield. The opening of X120 at Kirkfield generates this hypothesis, with the opening of 480 at Kirkfield plus X220 and X320 at Rosebank confirming it. Related to these events, it can be seen from summaries 3 and 8 that the protections operated at each end of the circuit (note that KIRKFIELD (ROSE) means that the activity has been declared at Kirkfield on the Rosebank circuit). Additionally, intertrip signals were received (summaries 5 and 11). The trip relays being reset are also indicated (summaries 6 and 13). These hypotheses capture the information which interests the protection engineers in relation to isolation of this circuit. The circuit also reclosed, as indicated in event summary 10. The expected autoswitching activity was indicated at each end of the circuit as identified by summaries 12 and 14.

In addition to the Kirkfield to Rosebank circuit there were events of interest on the Rosebank to Crossford circuit. Summary 1 indicates that the Crossford to Rosebank

1. **13:08:14.88**
(CROS (ROSE)) ISOLATED

2. **13:08:14.85**
TRIP RELAYS RESET AT CROSSFORD (ROSE)

3. **13:08:14.71**
SUCCESSFUL PROTECTION OPERATION AT KIRKFIELD (ROSE)

4. **13:08:14.74**
(ROSE (KIRK), KIRK SGT2) ISOLATED

5. **13:08:14.76**
FIRST AND SECOND INTERTRIP RECEIVED AT KIRKFIELD (ROSE)

6. **13:08:14.71**
TRIP RELAYS RESET AT KIRKFIELD (ROSE)

7. **13:08:14.70**
SUCCESSFUL PROTECTION OPERATION AT ROSEBANK (CROS)

8. **13:08:14.71**
SUCCESSFUL PROTECTION OPERATION AT ROSEBANK (KIRK)

9. **13:08:14.71**
TRIP RELAYS RESET AT ROSEBANK (CROS)

10. **13:08:35.87**
(KIRK SGT2, ROSE (KIRK)) RECLOSED

11. **13:08:14.76**
FIRST AND SECOND INTERTRIP RECEIVED AT ROSEBANK (KIRK)

12. **13:08:14.78**
SUCCESSFUL AUTOSWITCHING SEQUENCE AT KIRKFIELD (ROSE)

13. **13:08:14.72**
TRIP RELAYS RESET AT ROSEBANK (KIRK)

14. **13:08:14.79**
SUCCESSFUL AUTOSWITCHING SEQUENCE AT ROSEBANK (KIRK)

15. **Event initiated at 13:08:14.85 at CROS:**
Not all expected messages were received: Possible Solution(s):
1.SUCCESSFUL PROTECTION OPERATION AT CROSSFORD (ROSE)
The message CROS (ROSE) SECOND MAIN PROT OPTD ON was expected but not received
The message CROS (ROSE) SECOND MAIN PROT OPTD OFF was expected but not received

Table 3.3

feeder has been switched out. This has the associated protection events as indicated by summaries 7 and 15, with trip relay activity shown in summaries 2 and 9. However, the important element of the activity on this circuit is the fact that summary 15 shows only one main protection to have operated at Crossford. This hypothesis was produced as a result of the alarm at 13:12:40.60 causing APEX to time out as described in Appendix A, section A.2.2. Due to the nature of SCADA systems it cannot be determined whether this alarm is merely lost due to a telecommunications failure or if the protection actually failed to operate. If it is assumed that the protection did not operate then the difficulty arises in determining if it should have operated, or if the first main protection operated falsely. Within this case study three out of the four protections on the Crossford to Rosebank circuit operated, thus it seems feasible that the fourth should have operated. However, this can only be validated through the use of fault records and knowledge of how the protection was configured to operate. The Rosebank to Crossford circuit did not reclose.

In terms of data rationalisation, forty-nine alarms have been reduced to fifteen event summaries. The number of event summaries could have been reduced by combining rules. For example, the protection and trip relay rules could be combined to provide one summary covering protection activity with associated trip relay activity. The new rule would be :

```
Event "Protection and trip relays operated at <StationName>"
Priority 25
Expect
{
    Alarm "FIRST MAIN PROT OPTD"          ON    <StationName>
    Alarm "FIRST MAIN PROT OPTD"          OFF   <StationName>
    Alarm "SECOND MAIN PROT OPTD"         ON    <StationName>
    Alarm "SECOND MAIN PROT OPTD"         OFF   <StationName>
    Alarm "TRIP RELAYS TO BE RESET-E"     ON    <StationName>
    Alarm "TRIP RELAYS TO BE RESET-E"     OFF   <StationName>
}
```

Table 3.4

However, the level of event decomposition used was defined during knowledge elicitation meetings with protection specialists.

RESPONDD attempts to provide a fault diagnosis, based on the SCADA system data, which can be viewed as a scenario or disturbance overview. For the network in question (figure 3.4) the qualitative protection models used within RESPONDD are shown in table 3.5.

Substation	Circuit	Main Protection	RESPONDD Model Type
Crossford	Rosebank	First	Directional overcurrent
Crossford	Rosebank	Second	Directional overcurrent
Rosebank	Crossford	First	Directional overcurrent
Rosebank	Crossford	Second	Directional overcurrent
Rosebank	Kirkfield	First	Differential circulating current
Rosebank	Kirkfield	Second	Directional overcurrent
Kirkfield	Rosebank	First	Differential circulating current
Kirkfield	Rosebank	Second	Directional overcurrent

Table 3.5

The conclusion reached by RESPONDD was :

There was an earth or phase fault on Rosebank to Kirkfield::ln1 which is temporary which the protection equipment isolated.

There was also an earth or phase fault on Crossford to Rosebank::ln1 which is permanent or temporary which the protection equipment isolated. The alarms for Crossford::main protection 2 operated are missing.

Table 3.6

The Rosebank to Kirkfield fault was determined to be temporary due to the autoreclosure of the circuit without any subsequent operation of the protection. For the Crossford to Rosebank fault no decision could be made on whether the fault was temporary or permanent since there was no autoswitching mechanism configured.

Also, the phase and earth fault scenarios were combined into the one hypothesis since both cause the same activity to occur. Note that RESPONDD recognised the absence of the second main protection operation at Crossford.

By using APEX and RESPONDD forty-nine alarms were summarised as fifteen events of interest covering two simultaneous primary system faults.

3.5 Advantages of the Knowledge Based Module

The overall benefit of the knowledge based module is data rationalisation through the intelligent interpretation of SCADA system data. This can be decomposed into a number of individual advantages :

- Summarisation of incoming alarms into discrete events of interest.
- Identification of isolated plant within the power system network.
- Indication of the reclosure of isolated areas of the power system network.
- Provision of fault diagnostic information (which offers a disturbance overview).
- Identification of "missing" events which point to further required analyses.

The last point above is extremely significant in that it demonstrates one of the problems of interpreting SCADA system data. By the nature of SCADA systems if an expected alarm is not received then it begs the question of whether the telecommunications system has failed or the device did not operate. This was exemplified through the case study where an expected second main protection alarm did not arrive. To combat this problem other data sources need to be interrogated, which is the remit behind the model based module of this DSS.

The knowledge based module presents pertinent information to the protection engineers and alleviates the requirement for time consuming manual analysis of SCADA system data. Most importantly, this module offers on-line functionality and provides interpretation of the SCADA system data as a disturbance occurs. From the information provided by this module, the protection engineers can determine which protection schemes need to be analysed in more detail for problems such as slow clearance of faults or unexpected operation of a protection relay. Therefore, validation of protection operation is the next task which the DSS needs to tackle.

3.6 Chapter Summary

This chapter covered the necessity for decision support to unburden protection engineers when it comes to their data analysis tasks. Through a discussion on the role of protection engineers and their data analysis tasks the required functionality of the DSS was identified. Two modules, one knowledge based and one model based, were shown to be the proposed architecture for constructing the DSS. The knowledge based module was discussed with a relevant case study of its analysis of SCADA system data. Benefits of such knowledge based interpretation of SCADA system data for protection engineers were identified. The arguments developed throughout this chapter lead to the conclusion that the knowledge based interpretation of SCADA system data must be supported by interpretation of fault records with the aim of validating protection performance. Chapter 4 builds upon this and develops the case for a model based reasoning approach to the comprehensive validation of protection performance.

Chapter 4

Model Based Validation and Diagnosis of Power System Protection

4.1 Chapter Overview

The previous chapter of this thesis discussed the requirements of a DSS tailored for protection engineers. Through this it was identified that comprehensive validation of protection performance is required, using the detailed data available from fault recorders or equivalent devices.

This chapter proposes the expert system paradigm known as model based reasoning as an appropriate technique for the validation task. By examining research concerning the more specific area known as model based diagnosis (MBD), as applied to electronic circuits, the potential benefits of adopting such an approach for protection validation are identified. Following this, consideration is given to the application of the chosen MBD methodology, known as consistency based diagnosis, to power system protection. A feasibility study follows which comprises case studies of this technique applied to the validation and diagnosis of unit, distance and overcurrent protection schemes. Subsequently, the merit of this MBD technique is assessed with respect to implementation within the DSS.

A bibliographical overview of pertinent research concerning model based diagnosis is embedded within the sections presenting the principles and concepts underpinning this technique. Key papers within the domain of MBD are referenced and their relevance to this application assessed.

4.2 Introduction

As discussed in Chapter 3, protection engineers use the detailed data available from fault records (or equivalent) to support their comprehensive analysis and validation of protection performance. The availability of fault records is increasing in a drive to improve the data available to protection engineers. A better understanding of power system and protection behaviour is the expected outcome from this. However, this perceived benefit suffers from the fact that the limited number of protection engineers have an ever increasing amount of analyses to perform due to increased data availability. Therefore, in addition to knowledge based interpretation of SCADA system alarms, facilities are required to intelligently analyse protection performance using all the available data. This will cover instances where protection schemes seem to have failed (as in the case study presented in Chapter 3) to validating the timing of fault clearance when the expected protection relays, trip relays and circuit breakers have operated.

The comprehensive validation of protection system operation entails the comparison of expected protection operations with actual operations. Protection functionality can be modelled accurately from the scheme level to the operation of the protection relay, trip relay and circuit breakers. These models can range from logic based approaches to mathematical formulae or hybrid models. Given an accurate model of a protection relay's operating characteristics the recorded primary system analogues can be used as input and the model will predict the operation of the relay. Further models of trip relays and circuit breakers can then be used to predict the complete protection scheme operation. Recorded information about the actual protection operations can then be compared with the models' predictions. Therefore, the ability to model protection functionality combined with access to relevant data from fault records supports a model based reasoning approach to validating protection operation (Chapter 2, section 2.3.2.3).

Following the validation phase, some form of diagnosis may be required if the expected and actual behaviours differ. Thus, the DSS should not only validate protection operation but automatically diagnose any problem. Model based diagnosis (a subfield of model based reasoning) is able to validate operation and diagnose failures based on the same models.

This chapter discusses the technique of model based diagnosis and its application to this particular problem. The types of protection models which it could make use of are presented. In essence, this is a feasibility study into the value of this technique as part of the overall DSS.

4.3 Model Based Diagnosis

Model based diagnosis stems from research concerning model based reasoning. Its simplest definition is the determination of failures within a system or device based on some form of model. Research concerning logic based diagnosis has identified two key approaches [34]. The first of these is abductive diagnosis which is based on fault models. Knowledge based systems use fault models gleaned through experience with the device in question and case based systems are built around previous cases which can be viewed as "models" of past experience with faults.

The second approach is consistency based diagnosis. This precludes the use of fault models (or abductive approaches) and only uses knowledge concerning normal or expected behaviour of components. Consistency based techniques use models of functionality for diagnostic purposes. This is a sub-discipline of model based reasoning since knowledge of normal functionality suggests a detailed understanding of the system in question. Diagnosis then becomes the interaction between prediction and observation [10]. That is, the expected outputs should be consistent with those predicted. A model is used to predict the expected behaviour (of a device or a system) which is then compared with the observed behaviour. Any discrepancy between these indicates some failure in the system whereas no discrepancy validates the device or system operation, given an accurate and validated model. This concept is shown in figure 4.1 (from [10]). This approach is described as diagnosis from first principles [9] [35]. If a discrepancy is detected then a number of techniques can be used to diagnose the particular failure being experienced.

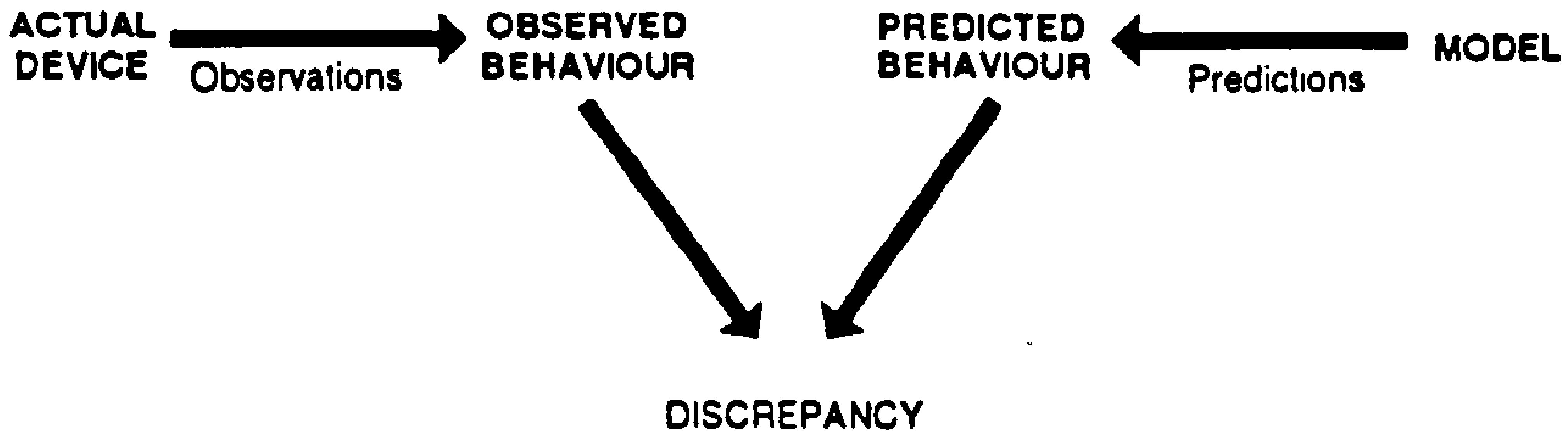


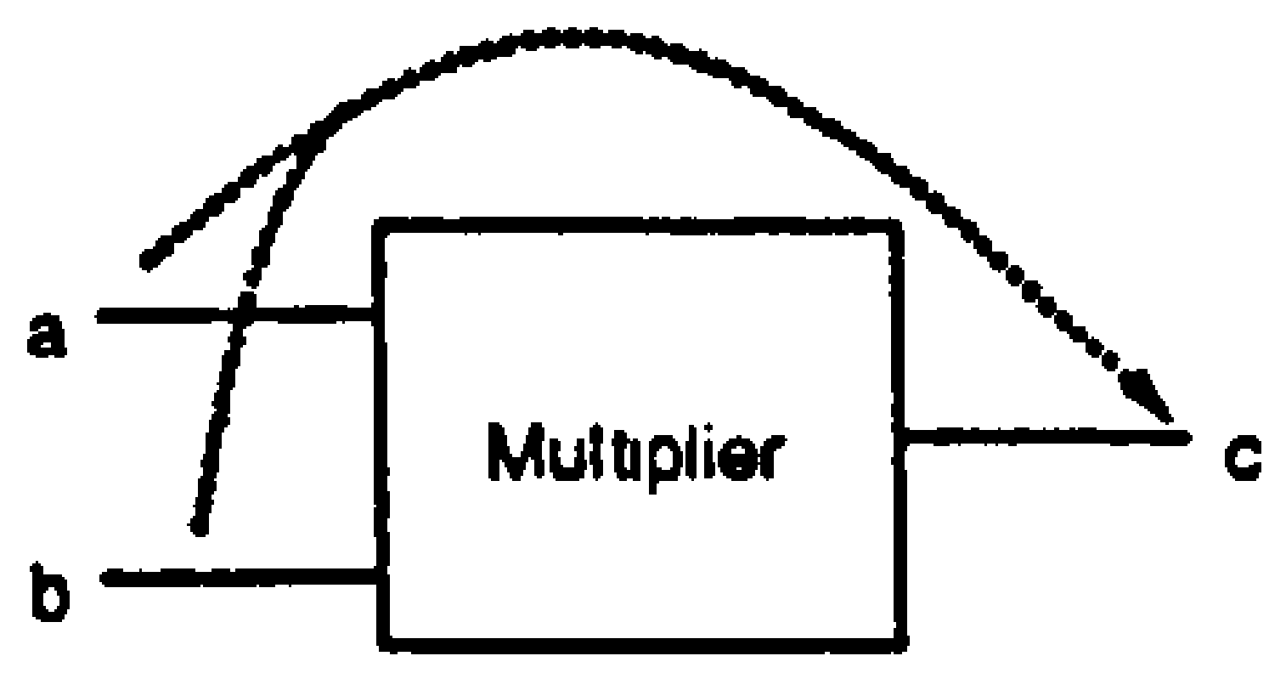
Figure 4.1: The concept of consistency based diagnosis.

4.3.1 Consistency based diagnosis

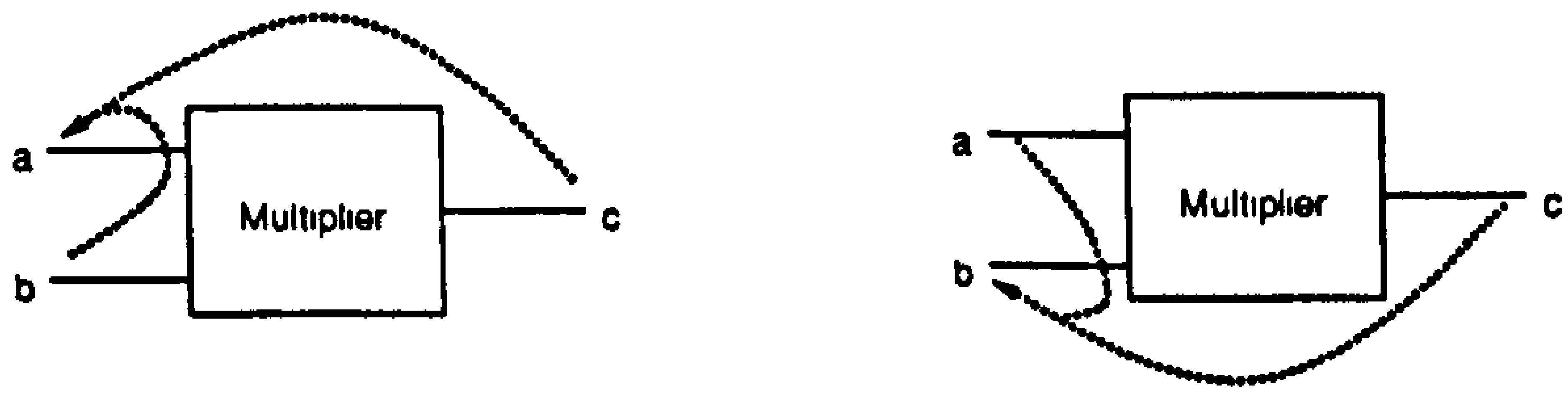
The earliest consistency based diagnostic system was the result of research by Johan de Kleer within the AI Laboratory at Massachusetts Institute of Technology. The resulting program INTER diagnosed faults in electronic circuits [36]. Following this work a number of techniques and systems were reported within the domain of consistency based reasoning. The key systems were developed by Reiter [9], de Kleer [11], Genesereth [12] and Davis [35].

There are two general techniques which underpin most of the research in this field. The first of these is the use of models of structure, behaviour and function (as described in Chapter 2, section 2.3.2.3). Each component model is used and the bidirectionality of its behaviour is exploited. For example, consider a multiplier. The path indicated in figure 4.2(a) demonstrates the normal operation of the multiplier.

That is, $a\ x\ b\ =\ c$. However, two more possibilities exist (figure 4.2(b)). Given c and a, $b = c \div a$. Also, given c and b, $a = c \div b$.



(a) Forward propagation of values



(b) Backward propagation of values

Figure 4.2: Propagation of multiplier inputs and outputs:(a)Forward propagation of values (b)Backward propagation of values.

By utilising such relationships the models can be used to predict the expected output from known inputs. And equivalently, expected inputs can be calculated from known inputs and outputs. This is exploited within consistency based approaches to diagnosis.

The second general technique is the decomposition of the diagnostic process into three fundamental tasks [10]. These are :

- Hypothesis generation.

  The determination of the possible faults which could explain the observed behaviour of the system under study.

- Hypothesis testing.

  Each of the possible faults must be tested to determine if it completely explains the observations from the system under study.

- Hypothesis discrimination.

  Often multiple diagnoses are produced. Therefore, the additional information required to distinguish between them must be identified.

4.3.2 Consistency based diagnostic systems and techniques

Three consistency based diagnostic systems will be discussed which cover two main methodologies. These are separated by their approach to hypothesis testing. The method reported by Davis [10] [35] uses constraint suspension to test hypotheses whereas Genesereth [12] and de Kleer and Williams [11] [37] [38] combine hypothesis generation and testing. To analyse the differences in these approaches a reference system to diagnose failures within is useful. To be consistent with the literature in this area [10] [11], the commonly used multiplier-adder circuit will be the test system (figure 4.3).

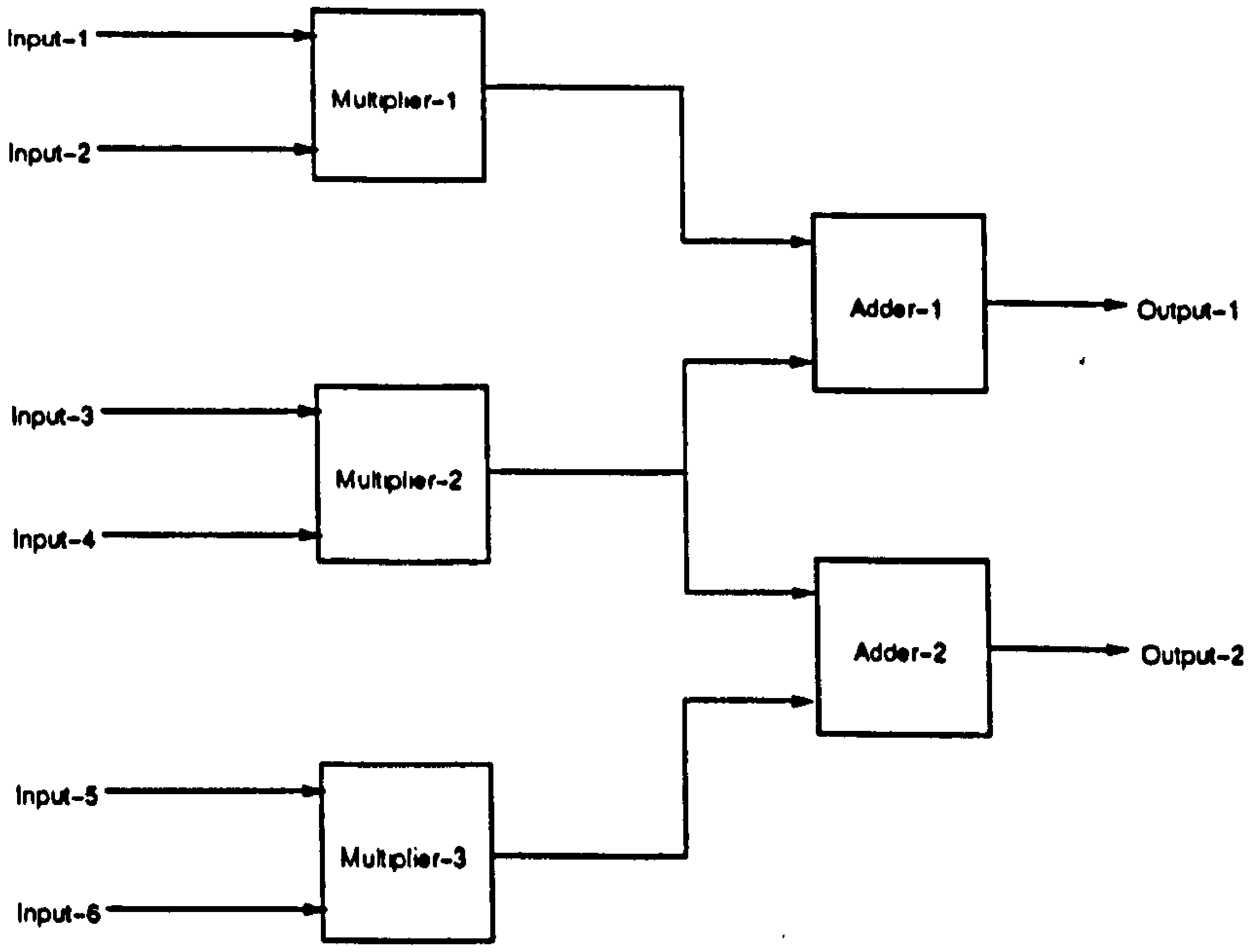


Figure 4.3: Multiplier-adder test system.

The behaviours of the two devices are easily modelled :

$$\begin{aligned}\text{Adder-x} &= \text{Input-y} + \text{Input-z}\\ \text{Multiplier-x} &= \text{Input-y} \times \text{Input-z}\end{aligned}$$

Use of such a test system with relatively simple functionality facilitates explanation of the diagnostic methodology.

4.3.2.1 Diagnosis using constraint suspension

If the test system is taken to have the inputs as shown in figure 4.4 then the expected outputs can be predicted by using the model. The observed outputs are shown in the same figure.

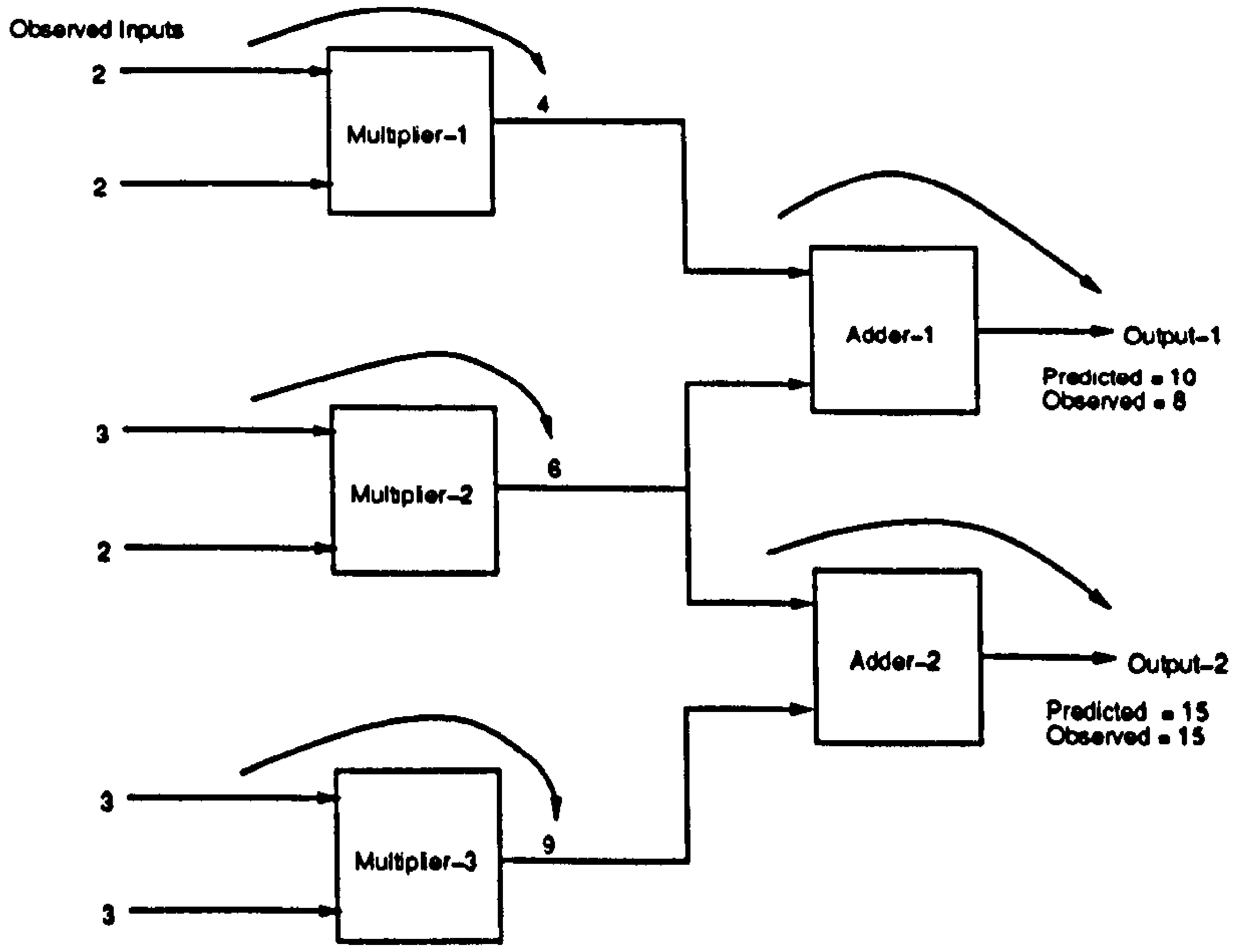


Figure 4.4: Example of predicted and observed operation of multiplier-adder circuit.

A discrepancy is identified at Output-1 since the predicted and observed output are not consistent. Therefore, the route to Output-1 is traced and the contributing components are identified as Adder-1, Multiplier-1 and Multiplier-2. These are termed the *dependencies* for Output-1 as this value is dependent on their operation. If we consider possible component failures which could cause the discrepancy then obviously each of the components which make up the dependency chain are a possibility. From this three hypotheses arise: Adder-1 has malfunctioned; Multiplier-1 has malfunctioned; Multiplier-2 has malfunctioned.

Each of these hypotheses must be tested. This is the point at which constraint suspension is employed. To test the hypothesis that Adder-1 malfunctioning can cause all the inconsistencies, its constraints (i.e. bidirectional relationships/equations which characterise the component model) are removed (suspended). Following this the remainder of the circuit is tested for consistency by propagating the inputs and outputs in all directions, ignoring the effects of the suspended component. Testing the hypothesis that Adder-1 has failed is shown in figure 4.5. This circuit is seen to be consistent therefore Adder-1 failing would explain the observed behaviour of the circuit. Additionally, the symptom of the fault is known to be that, for inputs of 4 and 6, Adder-1 is producing an output of 8 (figure 4.4).

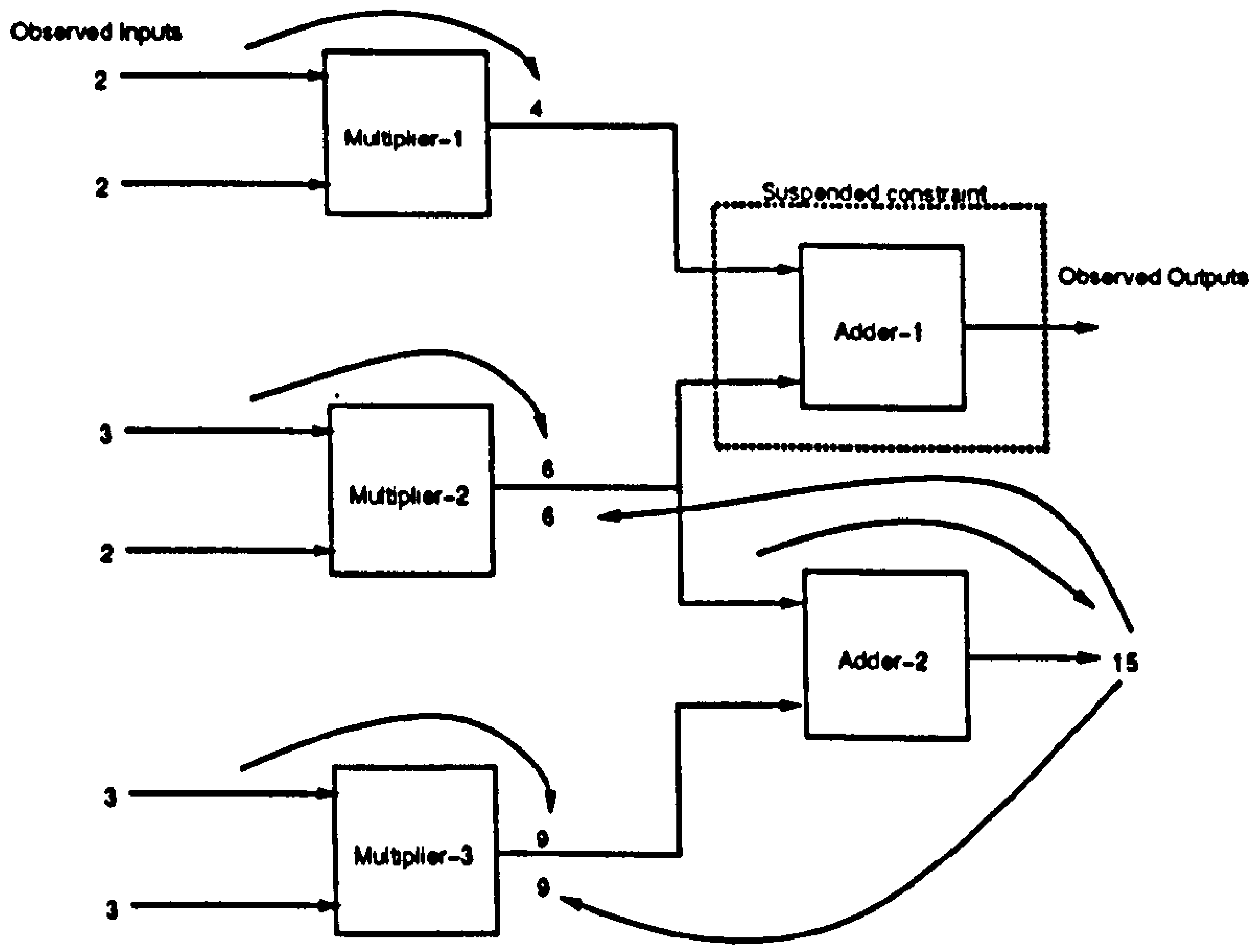


Figure 4.5: Suspension of Adder-1 constraints.

The hypothesis Multiplier-2 is tested in the same fashion by suspending the constraints associated with it (figure 4.6). An inconsistency is found at the output of Multiplier-2, therefore Multiplier-2 on its own would not explain the observed behaviour of the system hence it is not a valid hypothesis.

When the hypothesis Multiplier-1 is tested, the system is consistent (figure 4.7) with the symptom shown in figure 4.7 of Multiplier-1 generating an output of 2 when both input values are 2.

Through this diagnostic approach two possible single component failures have been identified: Adder-1 and Multiplier-1. The diagnosis was based solely on models of correct behaviour. It can be extended to include multiple failures by suspending multiple constraints simultaneously. A complete algorithm describing the methodology is detailed by Davis [35].

The next stage of the process is discrimination between the two hypotheses to determine which is the actual failure being experienced. The diagnostic system suggests the most appropriate test values to be taken (by probing of the circuit) which will identify the malfunctioning component [10] [35].

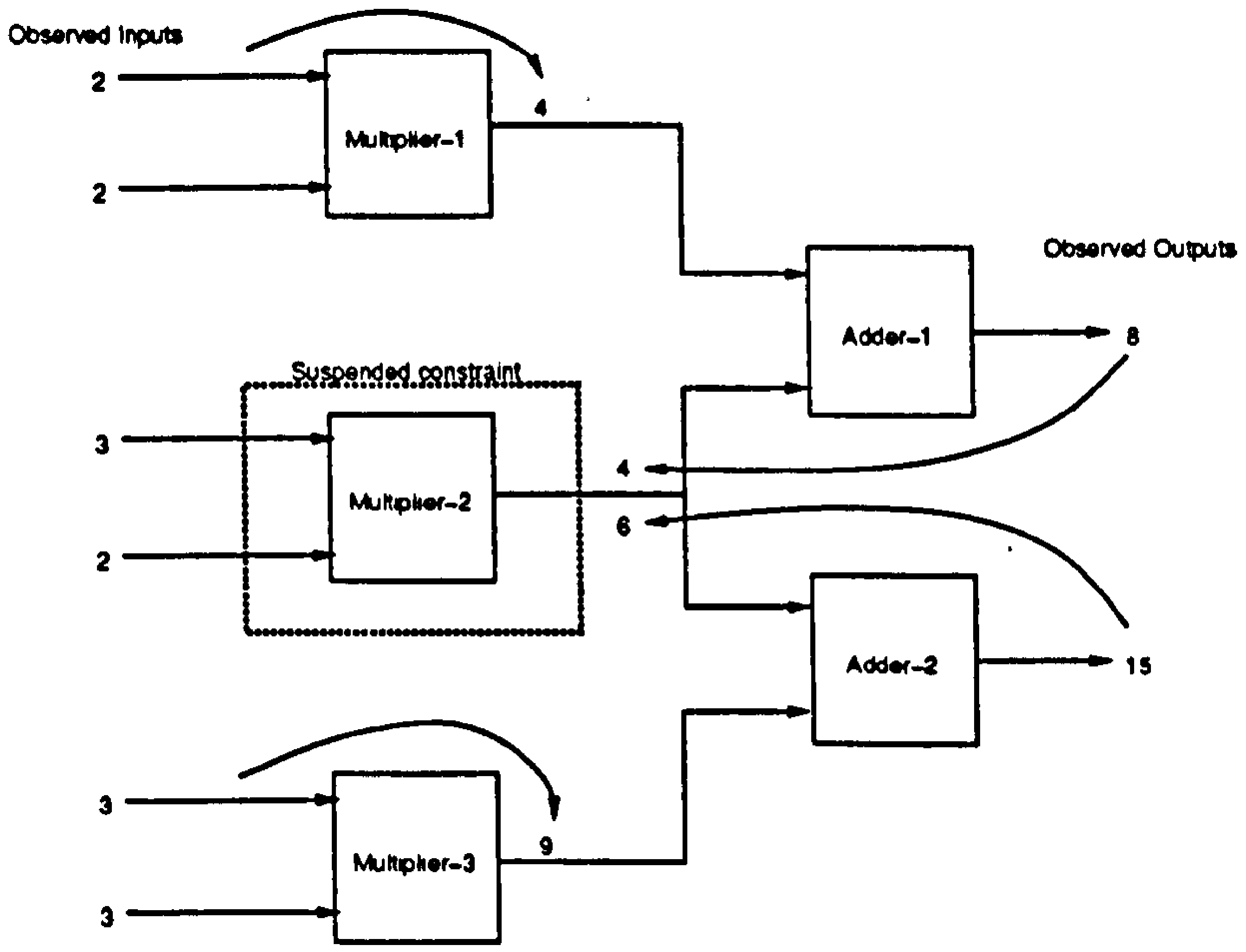


Figure 4.6: Suspension of Multiplier-2 constraints.

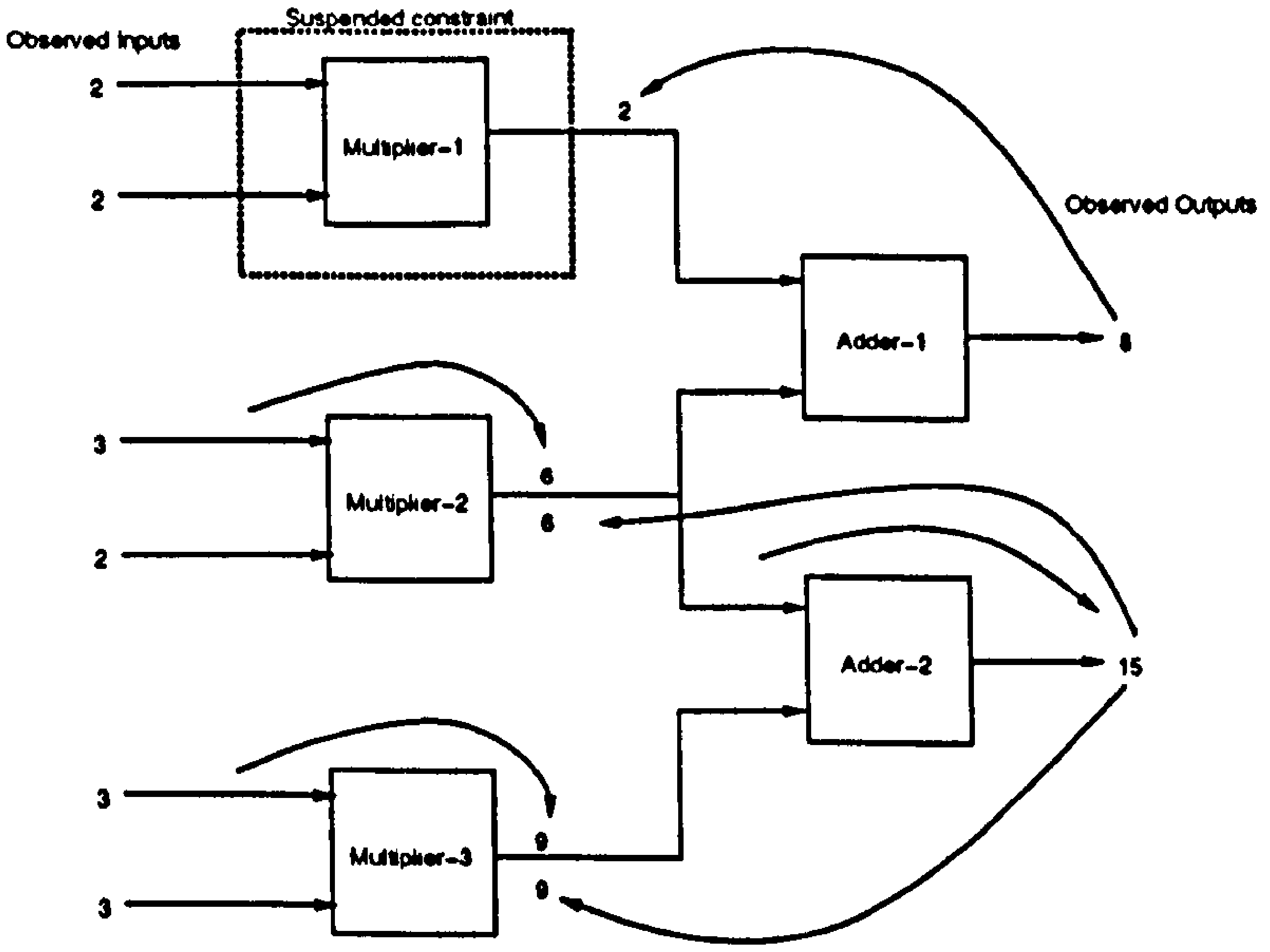


Figure 4.7: Suspension of Multiplier-1 constraints.

4.3.2.2 Combining hypothesis generation and testing

When discussing the consistency based diagnostic systems DART [12], developed by Genesereth, and the General Diagnostic Engine (GDE) [11] [38] developed by de Kleer and Williams, Davis states that [10] :

> "DART and GDE integrate hypothesis generation and testing sufficiently that when viewed in terms of generate and test they are best considered systems in which all of the testing knowledge has been integrated into the hypothesis generator."

In explanation, Davis is stating that these systems do not have an independent test mechanism for hypotheses such as constraint suspension. Instead, this process is implicitly embedded in the hypothesis generation task.

DART is described as an "automated diagnostician" [12]. Given a set of symptoms (i.e. discrepancies within a system) DART generates a set of tests to be carried out on the system. The results of these are input to DART and through iteration of this process the fault is pinpointed. This is a generic methodology which can be used to diagnose faults in many modelled systems. However, the approach would not be appropriate for validating protection performance or diagnosing failures within protection schemes based on fault recorder data. This data is pertinent to the fault and gives a single input set of data which can be used during the diagnostic process. Suggestion of possible tests to place the protection device under would be inappropriate for those installed in the power system. Nevertheless, the DART program may be appropriate for protection testing after design and before installation. However, this is not the immediate application of the work being reported in this thesis.

The second approach to combining hypothesis generation and testing was proposed by de Kleer and Williams through their General Diagnostic Engine [11] [38].

This also analyses models of structure, behaviour and function. Unlike constraint suspension, GDE will automatically generate hypotheses covering single and multiple device malfunctions. This methodology will be explained through the same example used to discuss constraint suspension.

As the input values are propagated forwards through the model the output of each component is stored along with its *environment*. An environment is the assumptions which support the prediction. For example, take Multiplier-1 (figure 4.8) where the predicted output is dependent upon the assumption that this component has operated correctly. The notation for an environment is {Multiplier-1}, as shown in the figure. This means that the output 4 at that point in the network assumes that Multiplier-1 has operated correctly. Values which are observable have empty environments meaning that they do not assume correct behaviour of any component in the model. Therefore, prediction of the operation of Multiplier-1 generates the environments demonstrated in figure 4.8.

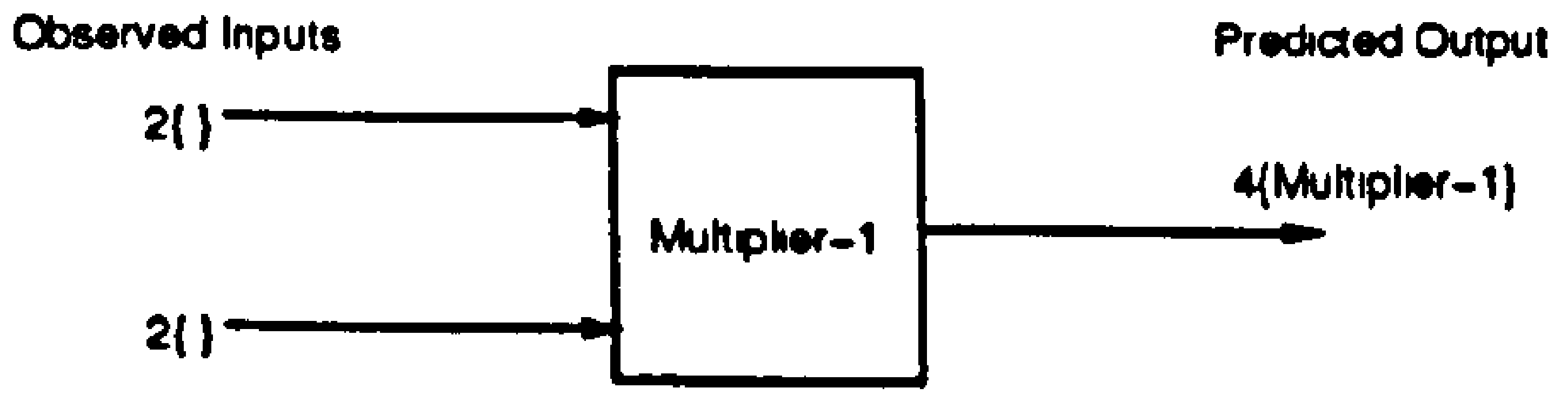


Figure 4.8: GDE environments.

This approach is taken throughout the model. The input observables are propagated forwards and the observable outputs propagated towards the inputs by manipulating the bidirectionality of the component models. If a correctly functioning multiplier-adder circuit is used, the environments would be as shown in figure 4.9. The model is then checked for consistency. In this case all predicted values and observed values are consistent so there is no problem with the circuit.

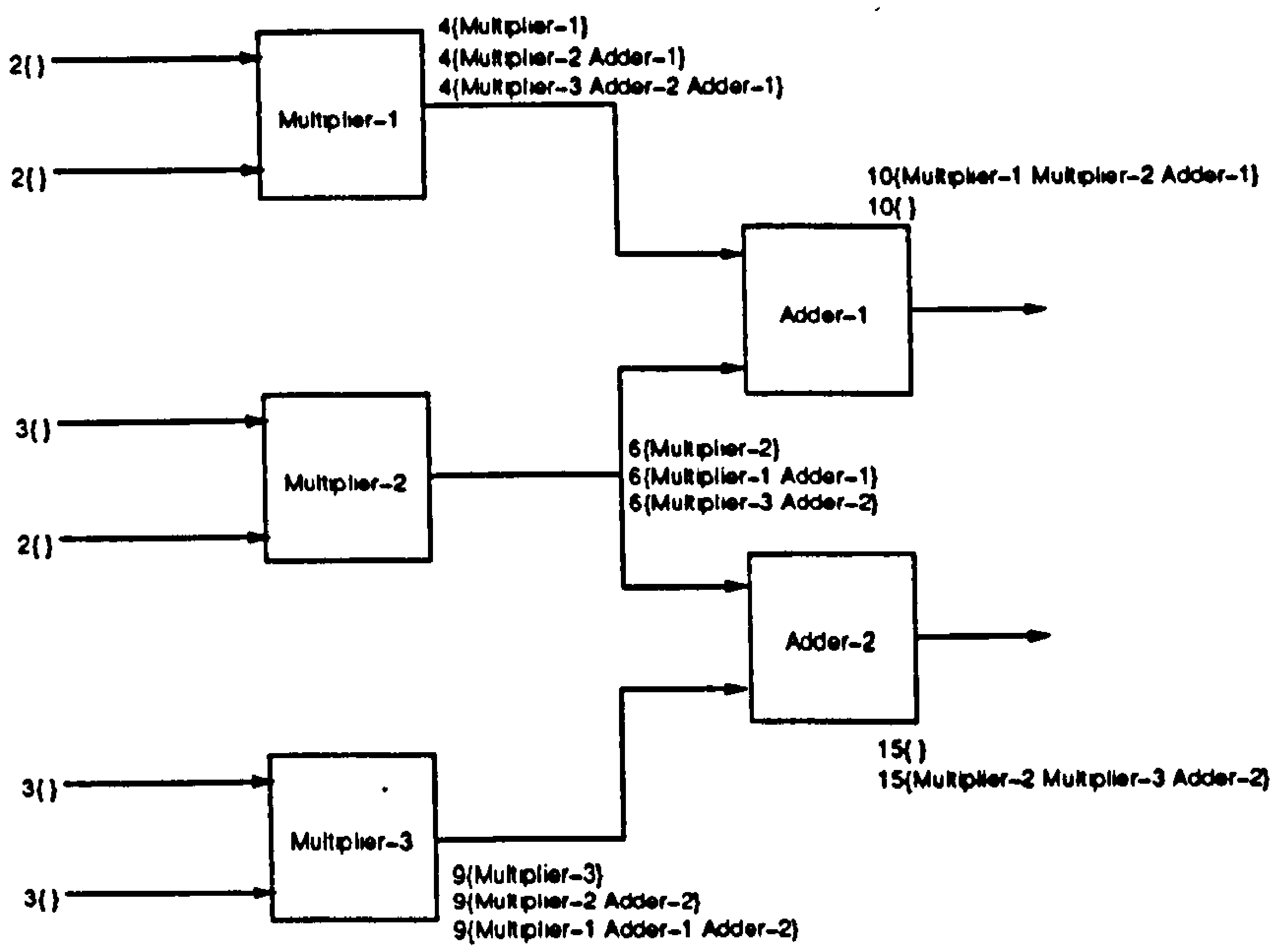


Figure 4.9: A consistent GDE model of the multiplier-adder circuit.

However, taking the example used for the explanation of constraint suspension gives the result shown in figure 4.10. If we consider the output from Adder-1 detailed as :

10{Multiplier-1 Multiplier-2 Adder-1}

then this is read as: the output from Adder-1 would be 10 assuming correct operation of Multiplier-1, Multiplier-2 and Adder-1.

In this example discrepancies exist at the outputs of Multiplier-1, Multiplier-2, Multiplier-3 and Adder-1. By recording the assumptions and manipulating inconsistencies then GDE is exploiting an Assumption based Truth Maintenance System (ATMS) to produce hypotheses [11] [39]. Truth maintenance systems are mechanisms for keeping track of dependencies and detecting inconsistencies [40]. This is a research field in its own right and outwith the particular scope of this thesis.

There are two inconsistencies (or discrepancies) at the output of Multiplier-1, as shown in table 4.1.

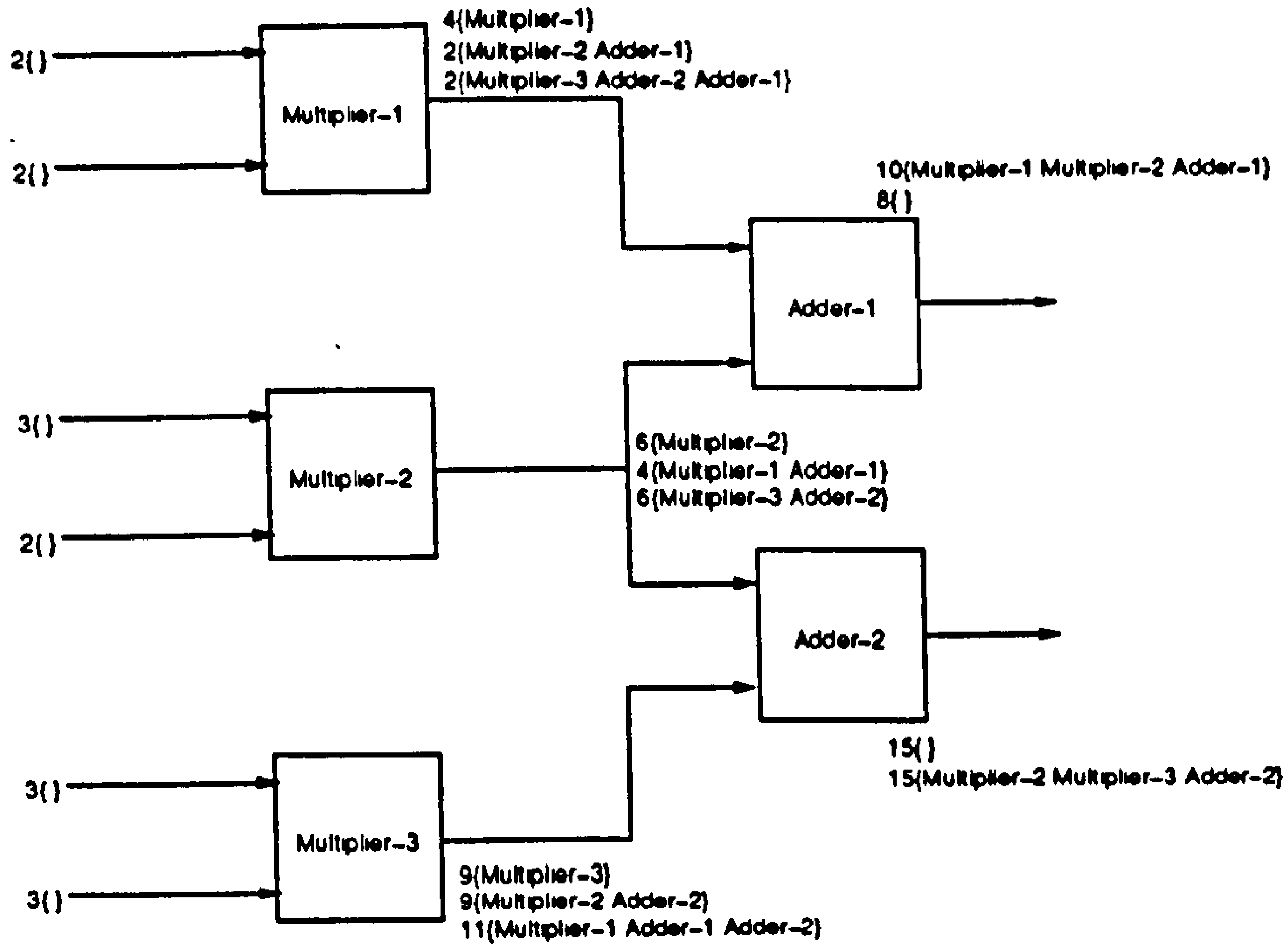


Figure 4.10: A GDE model of the multiplier-adder circuit with inconsistencies.

<u>Discrepancy 1</u>
4{Multiplier-1}
2{Multiplier-2 Adder-1}
<u>Discrepancy 2</u>
4{Multiplier-1}
2{Multiplier-3 Adder-1 Adder-2}

Table 4.1

Taking the first discrepancy each statement containing the predicted value and associated environment can be read as follows :

- 4{Multiplier-1}

  The value is 4 assuming correct operation of Multiplier-1.

- 2{Multiplier-2 Adder-1}

  The value is 2 assuming correct operation of Multiplier-2 and Adder-1.

GDE exploits the fact that both of these statements can not be true. Therefore, one of the components mentioned (Multiplier-1, Multiplier-2 and Adder-1) must have malfunctioned. This is classed as a *conflict set* and noted thus :

< Multiplier-1 Multiplier-2 Adder-1 >

Determination of conflict sets is the next stage of the GDE mechanism. The general rule is that for each discrepancy :

Conflict set = Union of environment sets .

The meaning attributed to a conflict set is that one of its member components must be malfunctioning. For the example under consideration the conflict sets in table 4.2 are produced.

Discrepancy :	4{Multiplier-1} 2{Multiplier-2 Adder-1}
Conflict set :	<Multiplier-1 Multiplier-2 Adder-1>
Discrepancy :	4{Multiplier-1} 2{Multiplier-3 Adder-1 Adder-2}
Conflict set :	<Multiplier-1 Multiplier-3 Adder-1 Adder-2>
Discrepancy :	10{Multiplier-1 Multiplier-2 Adder-1} 8{}
Conflict set :	<Multiplier-1 Multiplier-2 Adder-1>
Discrepancy :	6{Multiplier-2} 4{Multiplier-1 Adder-1}
Conflict set :	<Multiplier-1 Multiplier-2 Adder-1>
Discrepancy :	6{Multiplier-3 Adder-2} 4{Multiplier-1 Adder-1}
Conflict set :	<Multiplier-1 Multiplier-3 Adder-1 Adder-2>
Discrepancy :	9{Multiplier-3} 11{Multiplier-1 Adder-1 Adder-2}
Conflict set :	<Multiplier-1 Multiplier-3 Adder-1 Adder-2>
Discrepancy :	9{Multiplier-2 Adder-2} 11{Multiplier-1 Adder-1 Adder-2}
Conflict set :	<Multiplier-1 Multiplier-2 Adder-1 Adder-2>

Table 4.2

GDE is only interested in minimal conflict sets as this leads to identification of the minimal sets of faulted components. Therefore, duplicate and superset conflicts are removed. This results in two minimal conflict sets for this example :

<Multiplier-1 Multiplier-2 Adder-1>
<Multiplier-1 Multiplier-3 Adder-1 Adder-2>

Table 4.3

From the conflict sets the possible hypotheses are generated. These are termed *candidate sets*. This is the final stage of the hypotheses creation and the candidate sets indicate the components which must be failing to explain the observed behaviour of the system under study. The notation used is :

[Multiplier-1 Adder-1]

which means that Multiplier-1 and Adder-1 must both be malfunctioning.

Candidate sets are produced by set multiplication of the conflict sets. This produces the following candidate sets for the example diagnosis :

[Multiplier-1 Multiplier-1]	[Multiplier-1 Multiplier-2]	[Multiplier-1 Adder-1]
[Multiplier-1 Multiplier-3]	[Multiplier-2 Multiplier-3]	[Multiplier-3 Adder-1]
[Multiplier-1 Adder-1]	[Multiplier-2 Adder-1]	[Adder-1 Adder-1]
[Multiplier-1 Adder-2]	[Multiplier-2 Adder-2]	[Adder-1 Adder-2]

Table 4.4

Obviously, those containing repetition of the same component collapse to single fault candidates. Following this, superset and duplicate candidates are removed. The resulting candidate sets are as shown in table 4.5.

[Multiplier-1] [Adder-1] [Multiplier-2 Multiplier-3] [Multiplier-2 Adder-2]

Table 4.5

These hypotheses mean that the discrepancy between predicted and observed behaviour of the adder-multiplier circuit can be accounted for in the ways demonstrated by table 4.6.

Multiplier-1 has malfunctioned. OR Adder-1 has malfunctioned. OR Multiplier-2 AND Multiplier-3 have malfunctioned. OR Multiplier-2 AND Adder-2 have malfunctioned.

Table 4.6

GDE now suggests test points whose values would assist discrimination between the four hypotheses. For example, probing the actual value at the output of Multiplier-1 would differentiate between the two single failure hypotheses.

Research concerning the GDE system has been extended to consideration of using the consistency based approach in collaboration with known failure modes. The GDE+ system developed by Struss and Dressler [41] uses fault models following candidate set generation to assign probabilities to the hypotheses or to indicate those which are implausible. Further research by de Kleer and Williams produced the system Sherlock which also uses fault models within a GDE framework [37] [42].

4.3.3 Advantages of consistency based diagnosis

There are a number of advantages to be gained from using consistency based diagnosis. The first of these is that it is a model independent diagnostic process. That is, the models are independent of the diagnostic engine. Therefore, the diagnostic engine can be viewed as a shell which interacts with the models defining the system under study, as shown in figure 4.11.

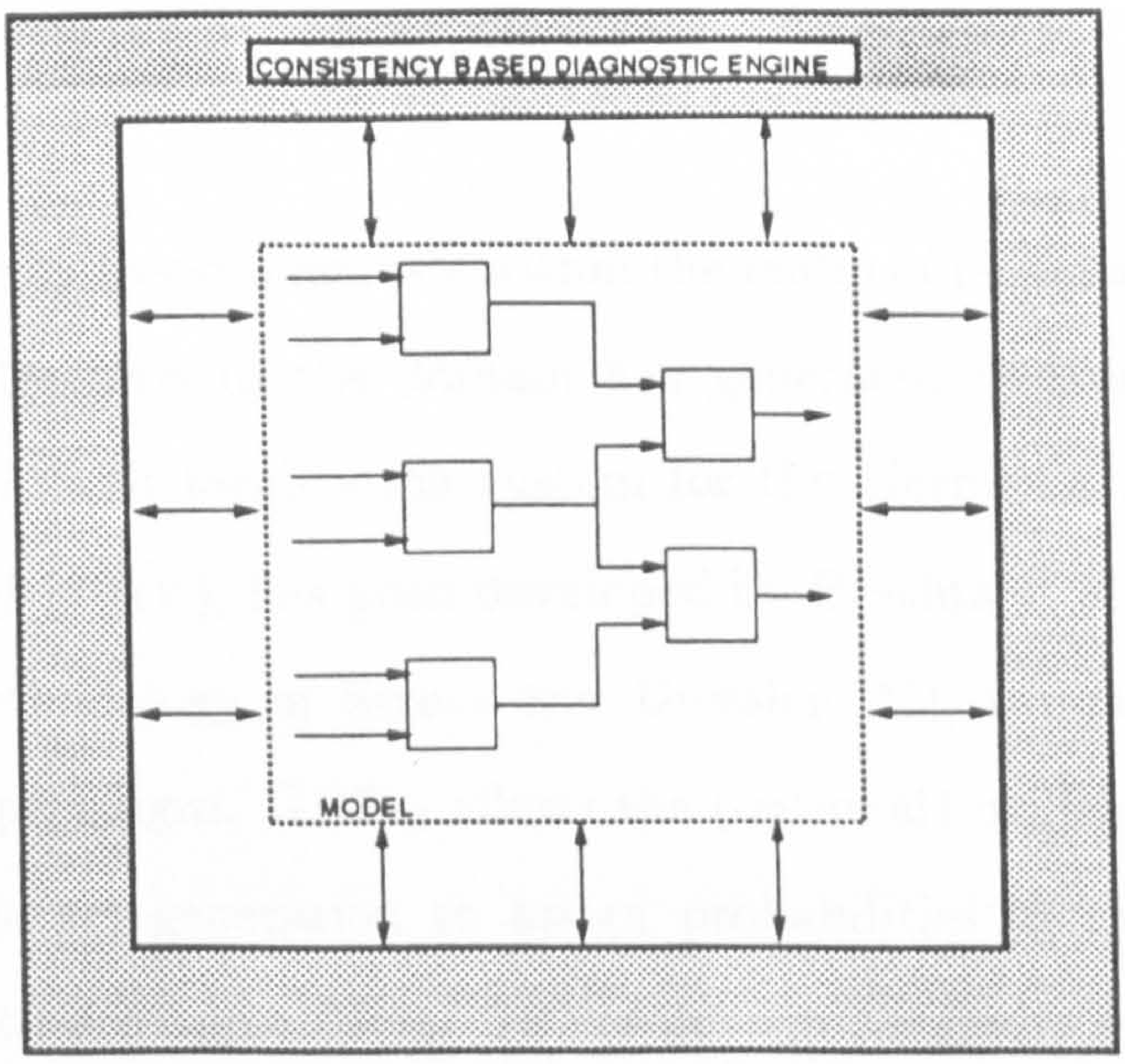


Figure 4.11: Interaction of consistency based diagnosis with models.

This allows the models to be in any form desired or appropriate, such as mathematical or logical. Alternatively the model of the complete system can be a hybrid of different types of component models. This facilitates maintenance of the diagnostic system and permits easier extension of its scope. Partitioning of the diagnostic engine and the models allows reuse of the models for various purposes such as simulation, design studies or training.

The consistency based techniques discussed are powerful in that novel faults (i.e. those previously unencountered) are identified. This is due to the methodology being based firmly on expected behaviour as opposed to fault models archived through experience. The techniques presented also cater for multiple failures which is important in diagnostic applications. Single points of failure can not be assumed to be the only possible malfunction type.

4.3.4 Power system applications of consistency based diagnosis

The use of consistency based diagnosis within the realm of power systems is becoming more apparent. Research in the domain has generated two prototype diagnostic systems. DPNet, a fault localisation system for the German transmission network (380kV, 220kV and 110kV), has been developed by Beschta et al. [43]. This is based on the GDE+ methodology of Struss and Dressler [41], which is an extension of the original GDE paradigm. GDE+ allows the (optional) utilisation of fault models following candidate set generation to assign probabilities to the hypotheses or to indicate those which are implausible. DPNet determines faults such as short circuits on lines and malfunctioning circuit breakers based on SCADA system data. From the literature it seems that correct protection operation is always assumed. Such an assumption is a limitation to the effectiveness of the DPNet system. This thesis deals with the issue that protection operation needs to be validated under many circumstances. Given that the German transmission system under study is protected by distance protection relays (with four zones of operation) only, it is obvious that a great deal of zone overlap for backup will occur. Accurate fault localisation requires this to be taken into account.

To discriminate between candidates (or hypotheses) DPNet uses the GDE+ technique of exploiting an information-theoretic method to determine the next measurement point which will reduce the number of possibilities [43] [41]. Therefore, DPNet starts by using only breaker activity, as indicated in the alarm stream, to generate the candidates. Then information (selected by the GDE+ mechanism) such as the direction of short circuit current on a line as indicated by the SCADA system data (i.e. towards or away from a certain busbar) is used to discriminate between the hypotheses.

The ESPRIT project ARTIST (Advanced Reasoning Tools for Model-based Diagnosis of Industrial Systems - EP5143) concerns the application of MBD to power systems. From this project a consistency based diagnostic system was developed by Tornielli et al. [44]. Building upon the GDE and GDE+ methodologies the prototype system diagnoses faults within a 220-380kV transmission network of an Italian region. Once more only distance protection relays are employed, each with four zones of operation. This diagnostic system is fed the following data [44] :

- For each protection relay, whether it has operated the associated breaker.
- The zone in which the short circuit was detected.
- For each circuit breaker, the status before the short circuit occurrence and after it has been isolated by the protection system.

This data is derived from SCADA system messages.

The diagnostic approach is to estimate the impedance measured by each protection relay which operated. These values are propagated and discrepancies collected. It is an "interval-based" approach. This term is used to describe the fact that the actual impedance measured by any relay is difficult to determine as a discrete and definite value. Therefore, an impedance range (or interval) is estimated based on the impedances which define the boundaries between different zones of operation. The impedance intervals are propagated through the model and inconsistencies lead to the generation of conflict and candidate sets. In this system busbars, lines and distance protection relays are modelled. Interestingly, Tornielli et al. model these components in terms of admittance with the viewpoint that it increases the model flexibility [44]. The GDE+ approach is utilised to exclude some of the implausible diagnoses.

Both of these diagnostic systems employ a consistency based approach based on the GDE system, working on models of structure, behaviour and function. The choice of a GDE based mechanism is merited since it automatically deals with single and multiple failures. This is the logical choice for a powerful diagnostic approach.

As the diagnostic mechanism is independent of the models, maintenance of the diagnostic systems is facilitated. This is in terms of both extensions to the transmission network being diagnosed and device/model updates. Both diagnostic programs are designed to be "system independent".

These model based systems utilise SCADA system data, or equivalent, for fault diagnosis at the power system level. Consequently, they can offer no better diagnoses than equivalent knowledge based systems (such as APEX and RESPONDD), due to their dependence on SCADA system (qualitative) data. In fact, neither appears to deal with protection schemes operating as backup or using intertripping. Furthermore, autoswitching activity is not exploited to determine the nature of the fault. These complex situations are catered for within RESPONDD. The stance taken within this thesis is that MBD lends itself to complex diagnoses where more detailed data is available. Hence, it offers the possibility of using the detailed (quantitative) data available to engineers from fault recorders and equivalent devices for validation/diagnosis of power system protection performance.

4.4 Model Based Diagnosis within the DSS

The consistency based approach to diagnostics has been presented as a powerful methodology, providing the system under study can be modelled in terms of structure, behaviour and function. Although the previous sections of this chapter have concentrated on diagnosis, consistency based methods also validate device operations. Following propagation of all the observables, if there are no discrepancies then the operation of the system under study has been validated. Therefore, such a diagnostic approach could be ideal for validating and diagnosing power system protection, depending on the suitability of protection models for integration with consistency based diagnosis methods.

4.4.1 Modelling power system protection for diagnosis

Models of power system functionality can be represented hierarchically from the individual components to the scheme level. Any protection scheme comprises individual devices such as current transformers, voltage transformers, protection relay, trip relay and circuit breakers. The behaviour of these combined with their interconnection defines the operation, or functionality, of the scheme (figure 4.12).

This is a flexible approach to protection modelling as it allows each model at the device level to be modelled in the most appropriate way. The interconnection level deals with input/output interactions allowing the scheme model to be composed of varying interplaying models (and model types). This offers a great deal of versatility when modelling power system protection. Libraries of different component types and varying model types can be created. To define a certain scheme the appropriate models from the libraries are linked together. Consider the unit protection scheme

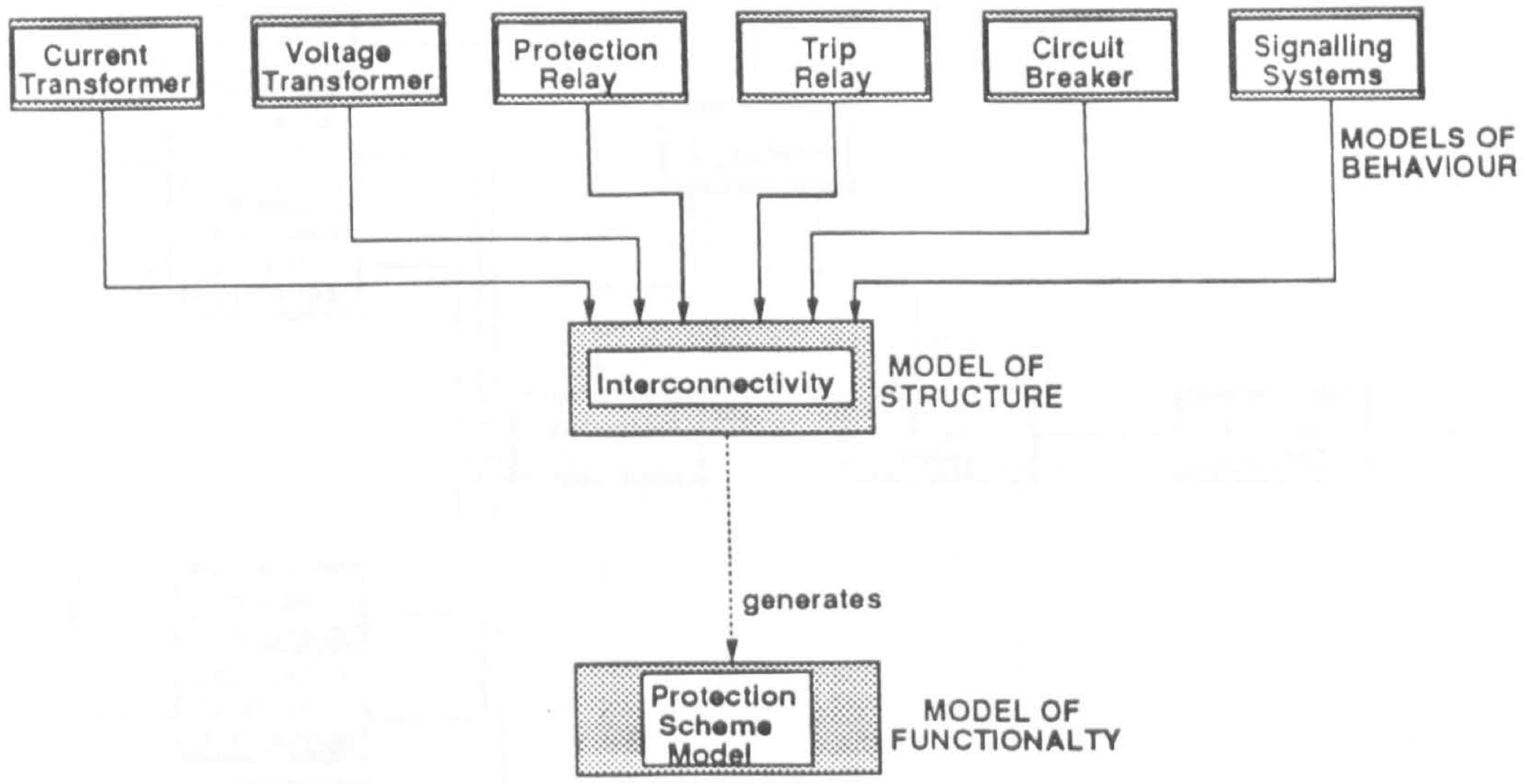


Figure 4.12: Generic approach to the modelling of protection schemes.

based on differential circulating current. This can be modelled as shown in figure 4.13. A similar example can be given for distance protection (figure 4.14).

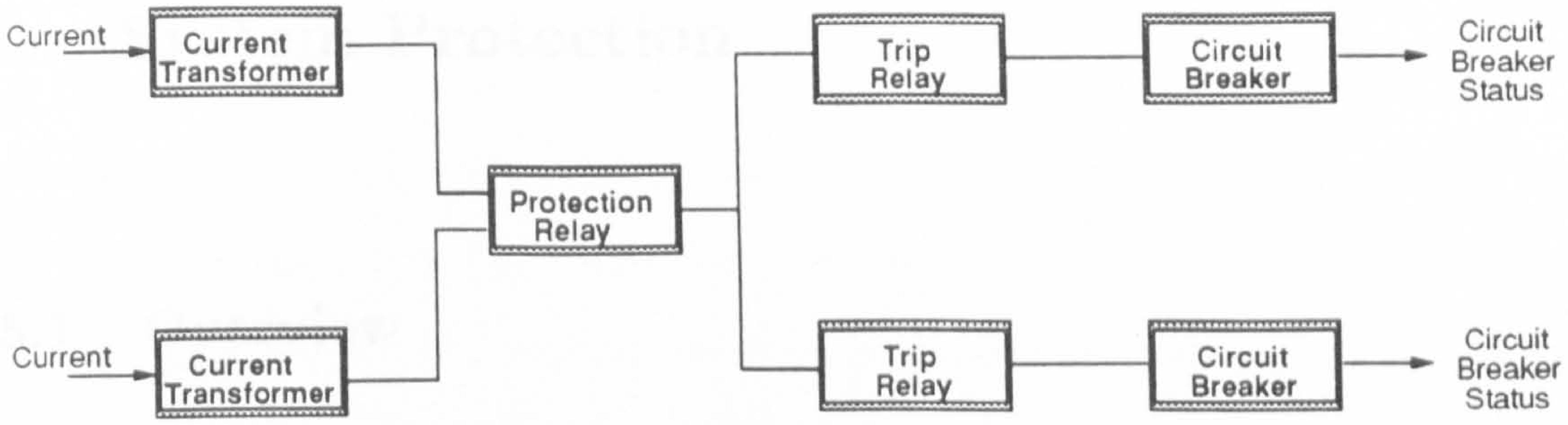


Figure 4.13: Model of differential circulating current protection scheme.

In fact, these models are of the structure, behaviour and function variety. Therefore, consistency based reasoning techniques should be able to interact with the protection models to either validate actual operation or diagnose failures. The input to the models needs to be more quantitative than is available from SCADA system data. Current and voltage inputs to the protection relays is required. Therefore, these models will use the detailed data available from fault recorders (or equivalent) as input.

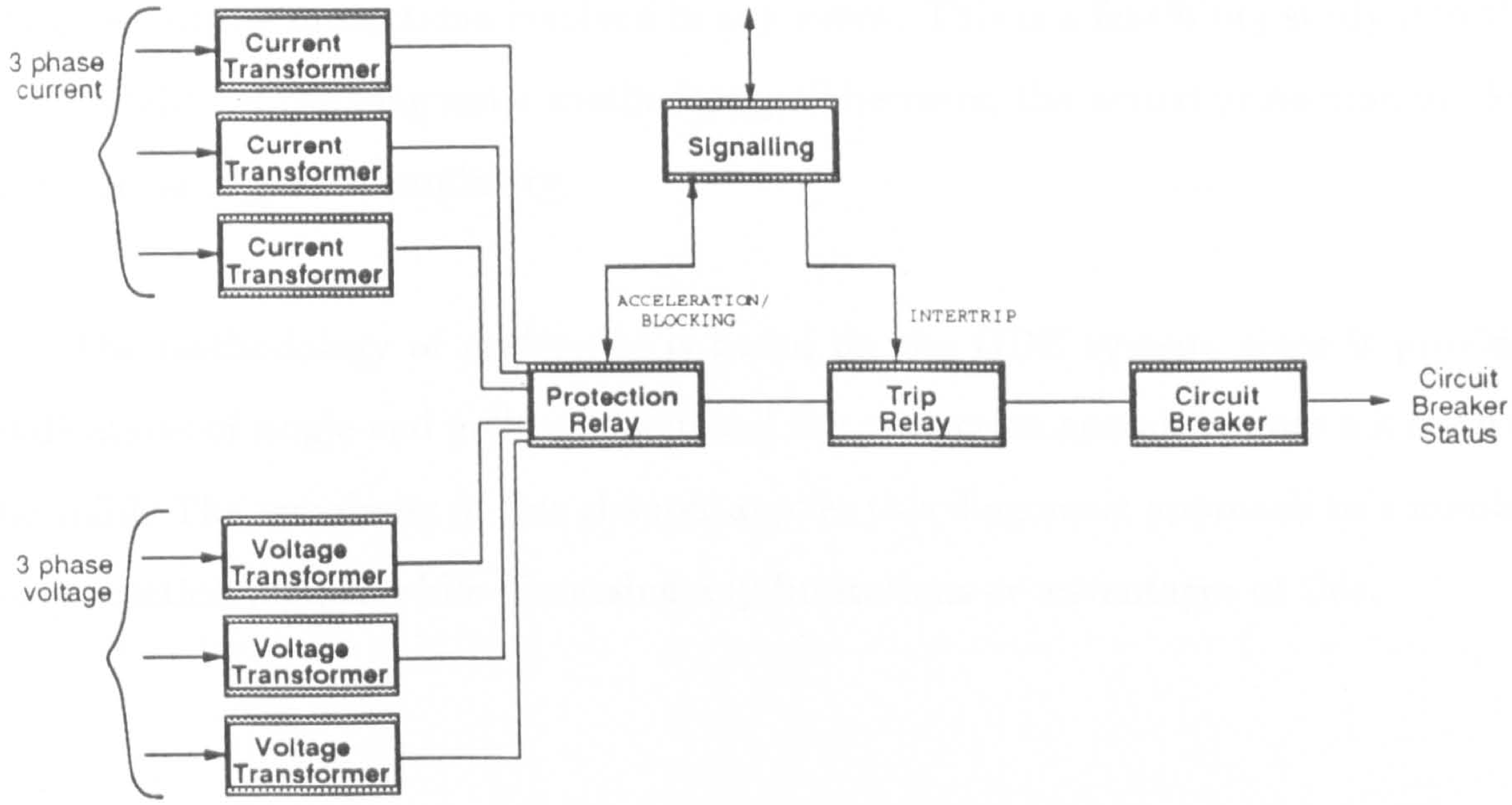


Figure 4.14: Model of distance protection scheme.

4.5 Consistency Based Diagnosis Applied to Power System Protection

4.5.1 Overview

Two key observations can be drawn from the discussion on MBD :

- Consistency based diagnosis is an appropriate method of validating and diagnosing systems which can be modelled in terms of structure, behaviour and function.
- Power system protection can be accurately modelled in terms of structure, behaviour and function.

Therefore, a novel use of the consistency based diagnostic approach would be to support the knowledge based module of the DSS by providing validation and diagnosis of the protections involved in any event. This is a feasibility study into the applicability of the diagnostic methodology. Therefore, the actual protection models will not be of great complexity.

The methodology of preference is based on the GDE system, since it provides indications of single and multiple failures if the protection operation does not seem to be valid. The remainder of this chapter applies this diagnostic approach to a number of protection models while discussing any limitations or advantages of this.

4.5.2 Consistency based diagnosis of a unit protection scheme

Figure 4.15 is a simplified single phase representation of the differential circulating current unit protection scheme (see Chapter 2, section 2.2.3). For this scheme, if the current transformers measure equivalent currents then the fault is known to be outwith the protected feeder. However, any appreciable difference in the measured currents cause the protection relay to operate and the consequent operation of the trip relays and the circuit breakers. This can be represented as a model of structure, behaviour and function as shown in figure 4.16.

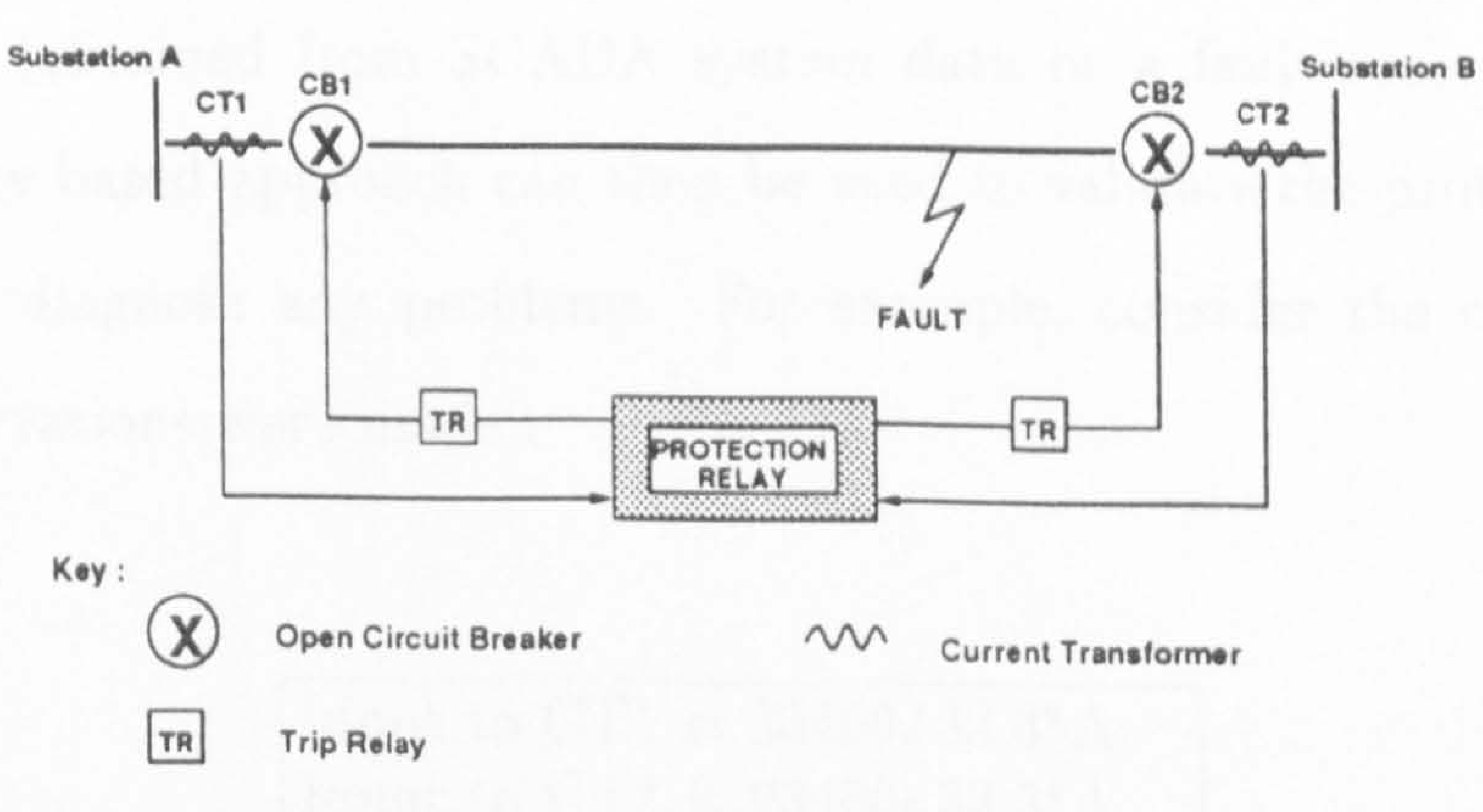


Figure 4.15: Differential circulating current unit protection.

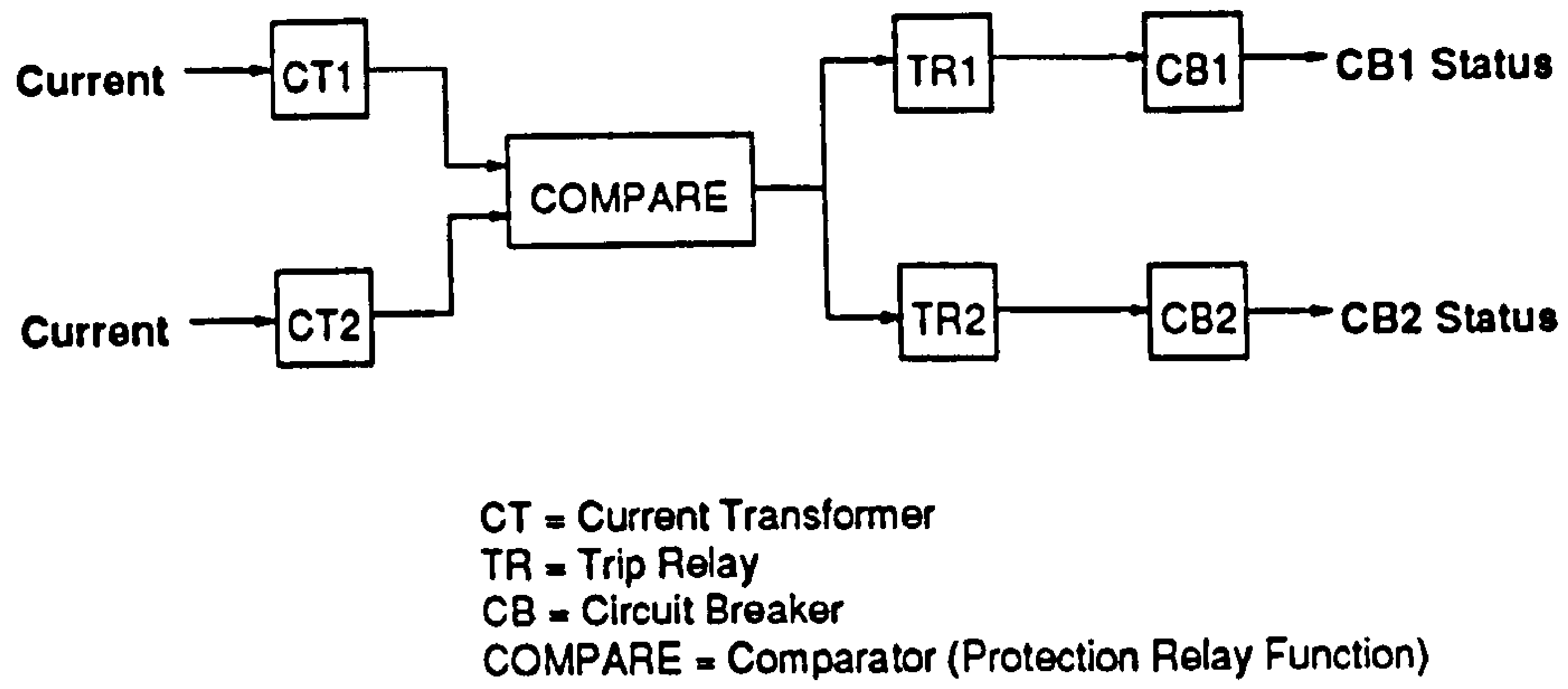


Figure 4.16: Model of differential circulating current unit protection.

The behaviour model for each component of the scheme model is given in figure 4.17.

CT

Input	Output
X	X

COMPARE

Input	Output
CT1=CT2	Not_Trip
CT1<>CT2	Trip

TR

Input	Output
Trip	Trip
Not_Trip	Not_Trip

CB

Input	Output
Trip	Open
Not_Trip	Closed

Figure 4.17: Component models for differential circulating current unit protection.

In the first instance the assumption is that only the fault currents measured by the current transformers (obtained from a fault recorder or equivalent) and the breaker states (obtained from SCADA system data or a fault record) are known. The consistency based approach can then be used to validate the protection scheme operation and diagnose any problems. For example, consider the case where the following observations were made :

Input to CT1 = $23400\angle 33.3°$A
Input to CT2 = $23400\angle 33.3°$A
CB1 status = CLOSED
CB2 status = CLOSED

Table 4.7

The propagation of these observables within the model is shown in figure 4.18. No discrepancies, or inconsistencies, arose as a result of the propagation process. Hence, the actual operation of the protection scheme is consistent with the model's predictions. In this case, the protection performance has been validated.

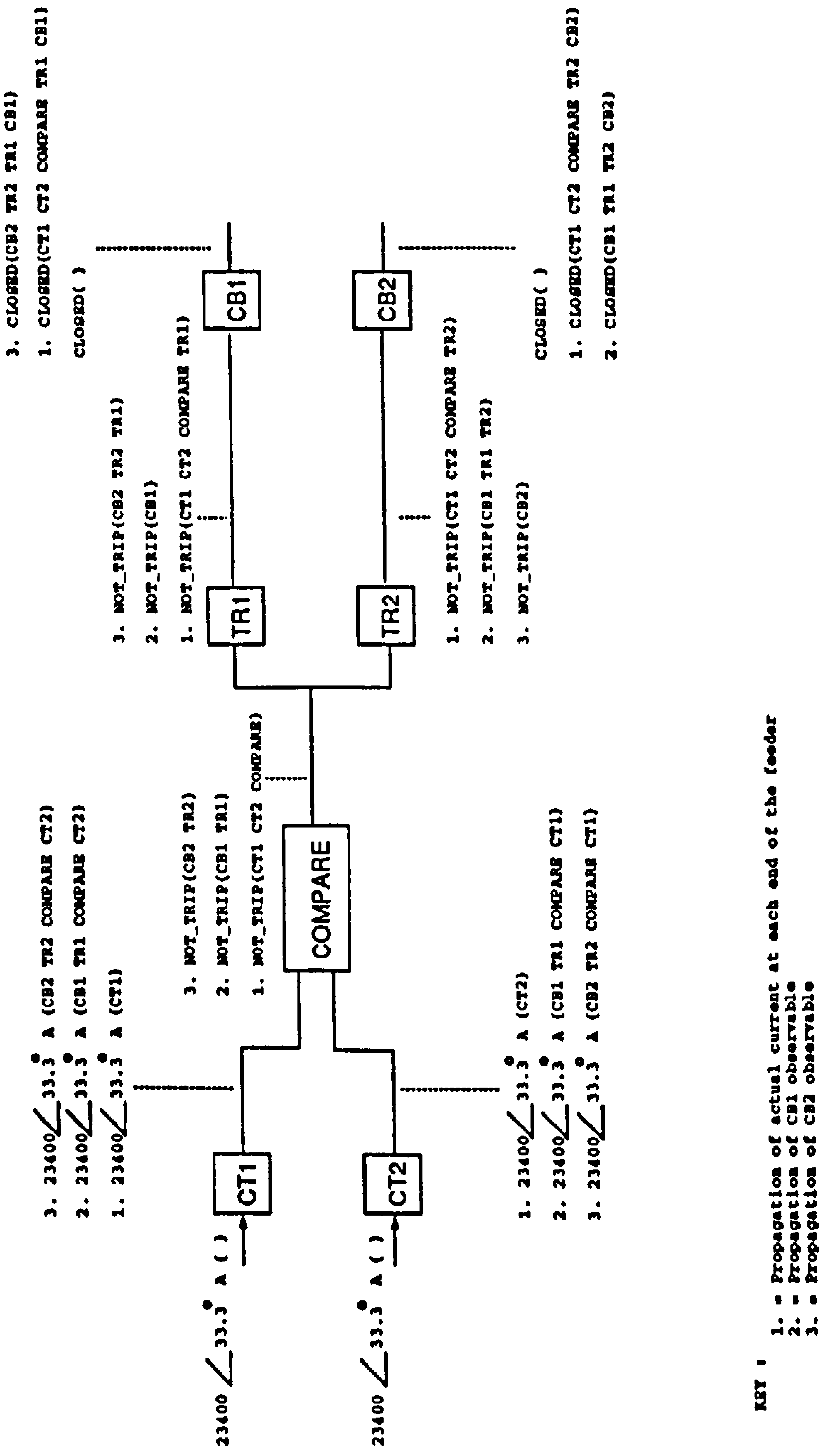


Figure 4.18: Consistency based validation of differential circulating current protection scheme operation.

In the second case the observables are :

Input to CT1 = $23400\angle 33.3^{\circ}$A
Input to CT2 = $32450\angle 215.6^{\circ}$A
CB1 status = OPEN
CB2 status = CLOSED

Table 4.8

The event indicated by the observables is that each current transformer has measured a different current, but only one circuit breaker has opened to isolate the fault. Propagation of the observables is demonstrated through figure 4.19. In this case a number of discrepancies are evident which means that the protection scheme has failed in some way. The conflict sets produced are :

<CT1 CT2 COMPARE TR2 CB2>
<CT2 COMPARE TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR2 CB2>
<CT1 COMPARE TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR2 CB2>
<TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR1 TR2 CB2>
<TR1 TR2 CB1 CB2>
<TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR2 CB2>
<TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR2 CB2>
<TR1 TR2 CB1 CB2>

Table 4.9

Duplicate and superset conflicts are removed leaving two minimal conflict sets :

<CT1 CT2 COMPARE TR2 CB2>
<TR1 TR2 CB1 CB2>

Table 4.10

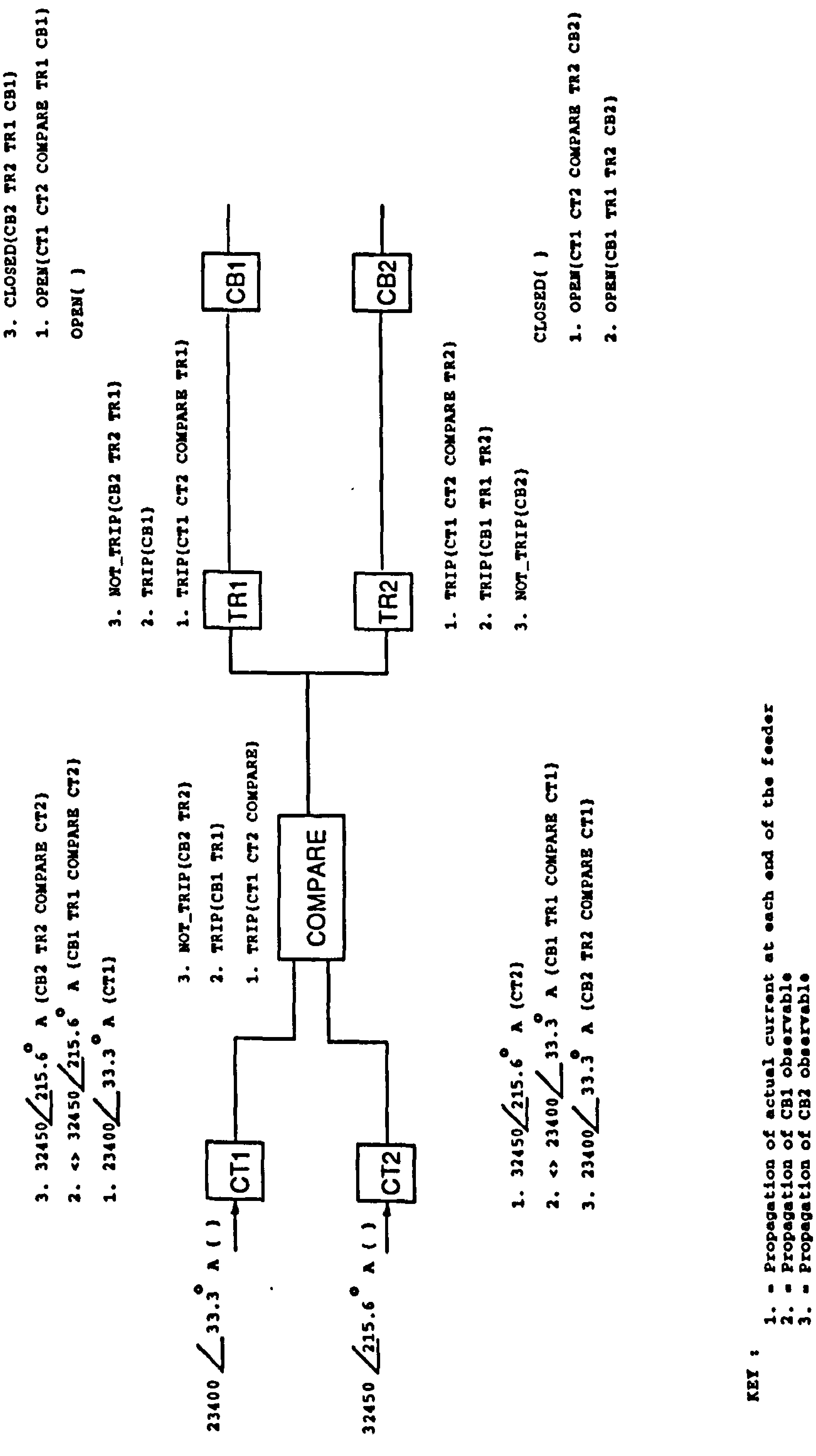


Figure 4.19: Consistency based diagnosis of differential circulating current protection scheme : Example 1.

Therefore we perform :

<CT1 CT2 COMPARE TR2 CB2> × <TR1 TR2 CB1 CB2>

which produces the candidate sets in table 4.11.

[CT1 TR1]	[CT1 TR2]	[CT1 CB1]	[CT1 CB2]
[CT2 TR1]	[CT2 TR2]	[CT2 CB1]	[CT2 CB2]
[TR2 TR1]	[TR2 TR2]	[TR2 CB1]	[TR2 CB2]
[CB2 TR1]	[CB2 TR2]	[CB2 CB1]	[CB2 CB2]
[COMPARE TR1]	[COMPARE TR2]	[COMPARE CB1]	[COMPARE CB2]

Table 4.11

The candidate sets [TR2 TR2] and [CB2 CB2] collapse to the single fault candidate sets [TR2] and [CB2]. Following this duplicate sets are removed leaving the minimal candidate sets as :

[CB2] [TR2]
[COMPARE CB1] [COMPARE TR1] [CT1 CB1]
[CT1 TR1] [CT2 CB1] [CT2 TR1]

Table 4.12

This means that: circuit breaker 2 malfunctioning on its own would explain the inconsistencies, and hence the observed values; trip relay 2 malfunctioning on its own would explain the observed values; the comparator and trip relay 1 both malfunctioning would explain the observed values (i.e. the comparator may have not tripped, but TR1 malfunctioned and generated a trip signal); etc.

Statistical and probabilistic methods could be used to determine the most likely candidate set (as in GDE+ [41]). Obviously, single failures are more likely than multiple failures, and certain device failures are more common than others. Moreover, knowledge based techniques could be employed to guide the final conclusion, as is the case in the GDE based system Sherlock [37] [42].

The next case considered is when both current transformers measure the same current, but the circuit breakers operate. Table 4.13 shows the observables.

Input to CT1 = 23400∠33.3°A
Input to CT2 = 23400∠33.3°A
CB1 status = OPEN
CB2 status = OPEN

Table 4.13

Propagation of these values throughout the model is shown in figure 4.20. A number of discrepancies arise which lead to the generation of fourteen conflict sets (table 4.14).

<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR2 CB2>
<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR2 CB2>
<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR2 CB2>
<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR1 TR2 CB2>
<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR1 TR2 CB1 CB2>
<CT1 CT2 COMPARE TR1 TR2 CB1>
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<CT1 CT2 COMPARE TR2 CB2>
<CT1 CT2 COMPARE TR1 TR2 CB1 CB2>

Table 4.14

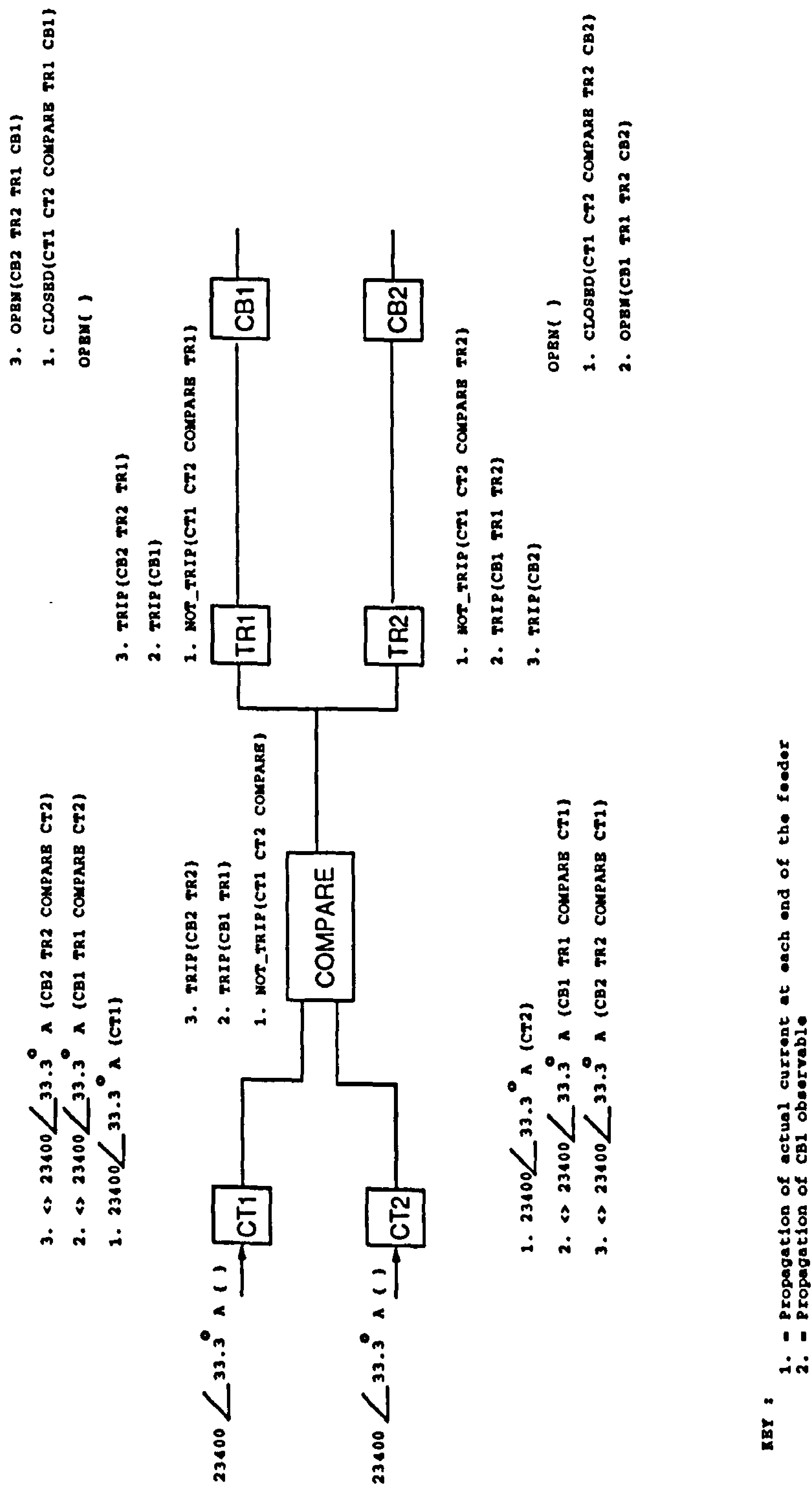


Figure 4.20: Consistency based diagnosis of differential circulating current protection scheme : Example 2.

These reduce to two minimal conflict sets :

<CT1 CT2 COMPARE TR1 CB1>
<CT1 CT2 COMPARE TR2 CB2>

Table 4.15

The minimal candidate sets generated from these two conflict sets are given in table 4.16.

[CT1] [CT2] [COMPARE]
[TR1 TR2] [TR1 CB2]
[CB1 TR2] [CB1 CB2]

Table 4.16

Given the four observables used seven hypotheses are generated. As discussed previously statistical or knowledge based techniques could be used to determine the most likely failure out of the seven. However, another aspect to consider is why the uncertainty arises. This is in fact due to a lack of observables at other points within the model. Given an indication of how other components actually behaved helps exonerate those unlikely to have been the cause of the protection scheme failure. This is akin to the hypothesis discrimination task within GDE [11]. Appropriate test points are identified to determine actual component behaviours. Essentially, these are observables which would have been desirable in the first instance. Therefore, increased observables should automatically narrow the possible hypotheses. This is proven through extending the previous example diagnosis to include extra observables, as indicated in table 4.17.

Input to CT1 = $23400\angle 33.3^\circ$A
Input to CT2 = $23400\angle 33.3^\circ$A
COMPARE status = TRIP
TR1 status = TRIP
TR2 status = TRIP
CB1 status = OPEN
CB2 status = OPEN

Table 4.17

Figure 4.21 shows the propagation of these values. From the discrepancies thirty-five conflict sets are generated. However, each one is a superset of a single conflict set :

<CT1 CT2 COMPARE>

Table 4.18

This results in the candidate sets shown in table 4.19.

[CT1] [CT2] [COMPARE]

Table 4.19

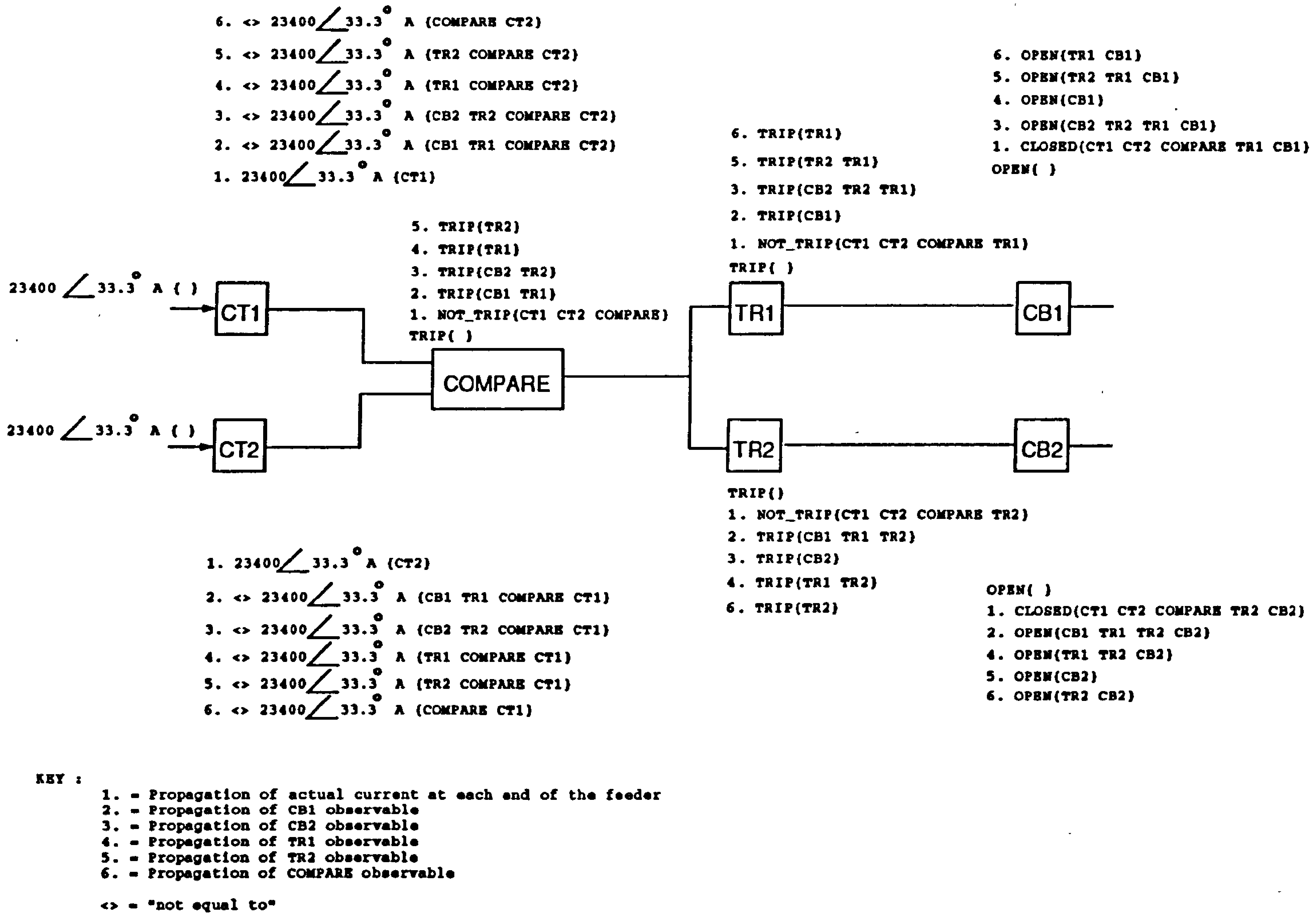


Figure 4.21: Consistency based diagnosis of differential circulating current protection scheme : Example 3 (using an increased number of observables).

These are a subset of the original hypotheses, hence extra observables have caused the possibilities to be narrowed. Considering this issue with a different angle shows the robustness of a consistency based diagnostic approach when faced with incomplete data sets. The previous two studies demonstrate that a reduction in observables extends the hypotheses, but does not make them incorrect. This can be demonstrated further if we consider the case where data availability is decreased :

Input to CT1 = 23400∠33.3°A
Input to CT2 = 23400∠33.3°A
CB1 status = OPEN

Table 4.20

In this instance the state of the second circuit breaker is unknown and propagation occurs as in figure 4.22. Once more, a single conflict set is produced :

<CT1 CT2 COMPARE TR1 CB1>

Table 4.21

Table 4.22 indicates the resulting candidate sets.

[CT1] [CT2] [COMPARE]
[TR1] [CB1]

Table 4.22

In essence, this means that any of the components up to and including CB1 could have malfunctioned, which would be obvious to a human diagnostician. No mention is made of TR2 or CB2 since there is no data of relevance to their operation. Although this may not seem to be a very useful diagnosis, an engineer could do no better with the given information. In fact, knowledge about the most likely faults would be used to decide which was the most probable. The same knowledge could be used within a post processing knowledge based hypothesis discriminator attached to the consistency based diagnostic system.

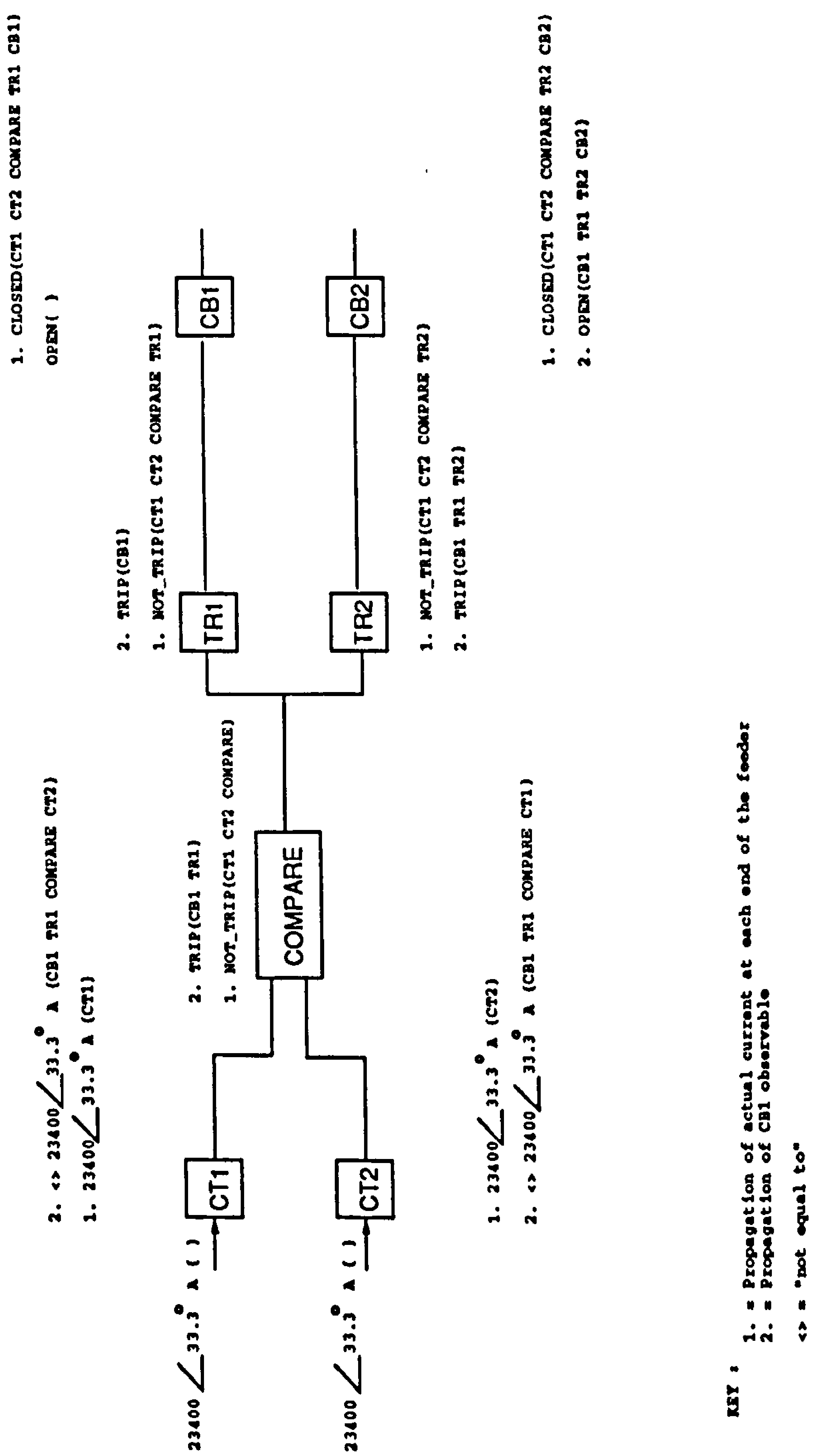


Figure 4.22: Consistency based diagnosis of differential circulating current protection scheme : Example 4 (using a decreased number of observables).

The importance of this example is that the diagnostic mechanism does not fail under poor data conditions or provide misleading hypotheses, which is a complaint about traditional rule based expert systems [45]. It "knows" its limitations and degrades gracefully.

4.5.3 Consistency based diagnosis of a distance protection scheme

The consistency based validation and diagnosis method was applied to a permissive under-reach transfer trip scheme for feeder protection (figure 4.23). This scheme arrangement interconnects two distance protection relays via a signalling channel. Under the condition where one of the relays detects a fault within zone one, it sends a signal to the relay at the remote end of the circuit. If the remote relay has detected a zone two fault and also receives a signal from the other relay then it will trip in a zone one time. This scheme offers faster clearance of faults on the feeder. However, both relays still offer backup protection for external faults.

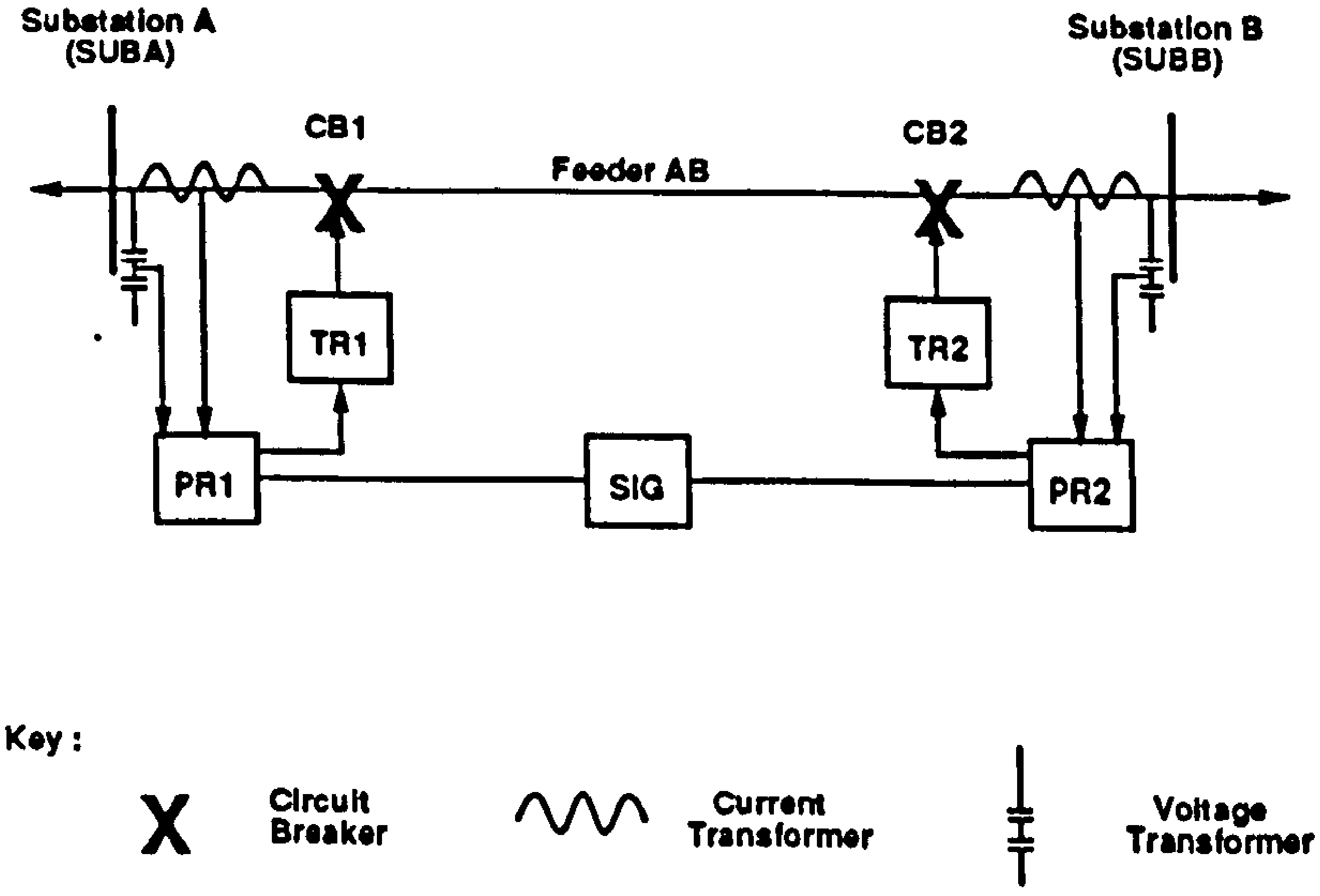


Figure 4.23: Permissive under-reach distance protection scheme.

The model of structure, behaviour and function for this protection scheme is assumed as shown in figure 4.24. Calculation of the fault zone from the three phase voltages and currents is a task of the protection relay model. Since the diagnostic methodology is the main concern of this discussion, the mathematical model to determine the operating zone is assumed and only the subsequent logical models are exploited in the example diagnoses. This does not detract from the analysis of the model based technique. The component models are shown in figure 4.25.

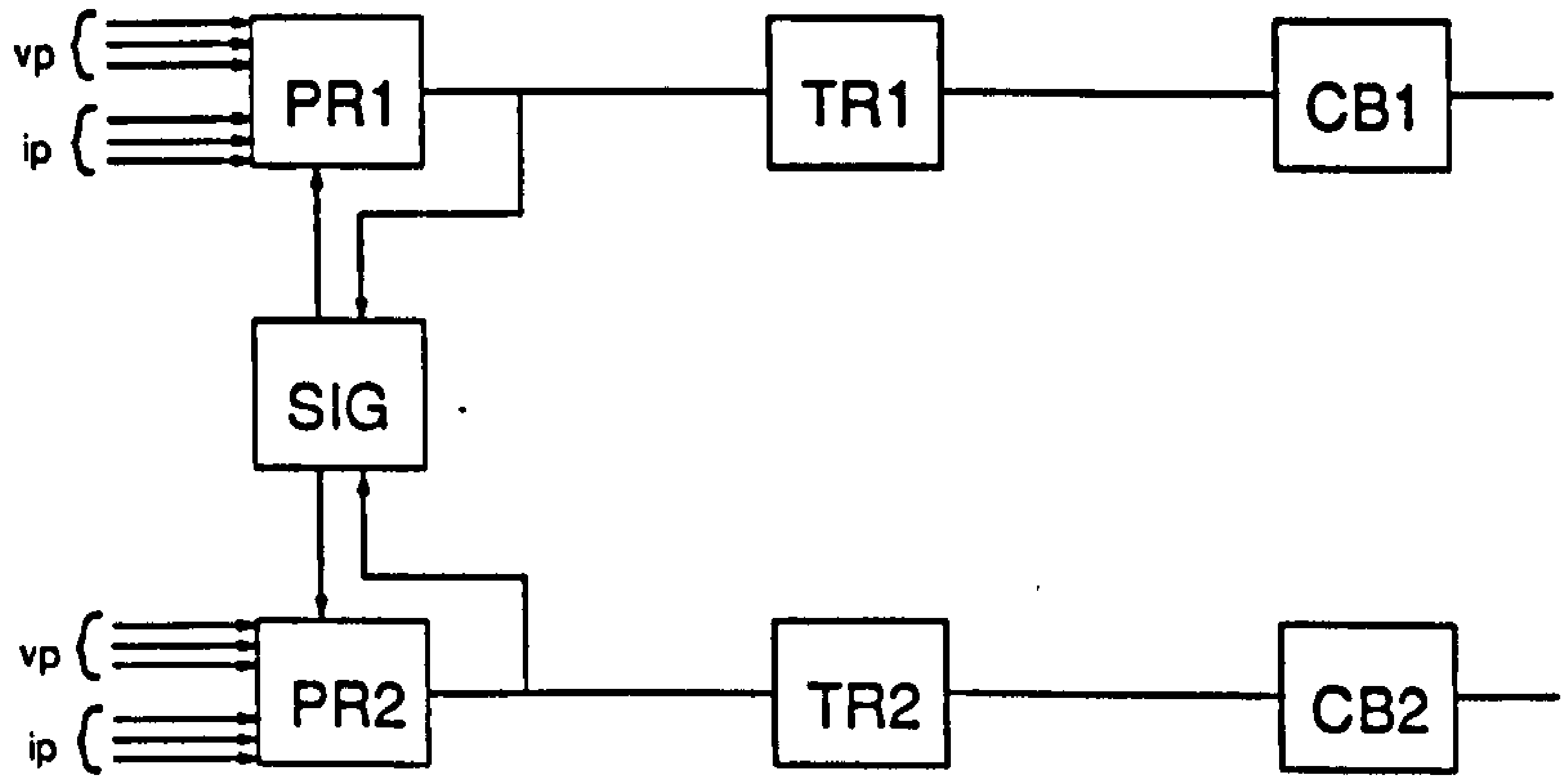


Figure 4.24: Model of permissive under-reach distance protection scheme.

Protection Relay

PR		
* Fault zone	Protection signal received	Time
Z1	-	t <= 70ms
Z2	Not_Trip	70ms < t <= 200ms
Z2	Trip	t <= 70ms
Z3	-	200ms< t <=400ms

Circuit Breaker

CB	
Input	Output
Trip	Open
Not_Trip	Closed

Protection Signalling

SIG	
Input (Time and Zone)	Output
t <= 70ms, Z1	Trip
t >70ms, Z1/2/3	Not_Trip

Trip Relay

TR	
Input (PR trip time)	Output
t <= 70ms	Trip
70ms<t<=200ms	Trip
200ms<t<=400ms	Trip
Not_Trip	Not_Trip

* Effective fault location in terms of distance from substation

Figure 4.25: Component models for permissive under-reach distance protection scheme.

The observables for this scheme would be derived from fault records and SCADA system data. Correct operation of the protection scheme is assumed in the first example, with table 4.23 containing the relevant observables.

PR1 operation = $\text{time}_{TRIP} \leq 70$ ms, zone 1
SIG input to PR1 = NOT_TRIP
TR1 status = TRIP
CB1 status = OPEN

PR2 operation = $\text{time}_{TRIP} \leq 70$ ms, zone 2
SIG input to PR2 = TRIP
TR2 status = TRIP
CB2 status = OPEN

Table 4.23

Propagation of the observables is demonstrated in figure 4.26. This model does not consider operating times for the trip relays and circuit breakers. Hence, the expected operating times for the protection relays can not be derived by propagating back from circuit breaker or trip relay observables unless either has not operated (i.e. in this circumstance it is evident that if the trip relay has not tripped then the protection relay should not have operated if everything was functioning correctly).

In figure 4.26 no discrepancies are found, therefore the protection scheme operation has been validated through the consistency based diagnostic method.

For the second example fault records and SCADA system data indicated the following operations :

PR1 operation = $\text{time}_{TRIP} \leq 70$ ms, zone 1
SIG input to PR1 = NOT_TRIP
TR1 status = TRIP
CB1 status = OPEN

PR2 operation = NOT_TRIP
SIG input to PR2 = TRIP
TR2 status = NOT_TRIP
CB2 status = CLOSED

Table 4.24

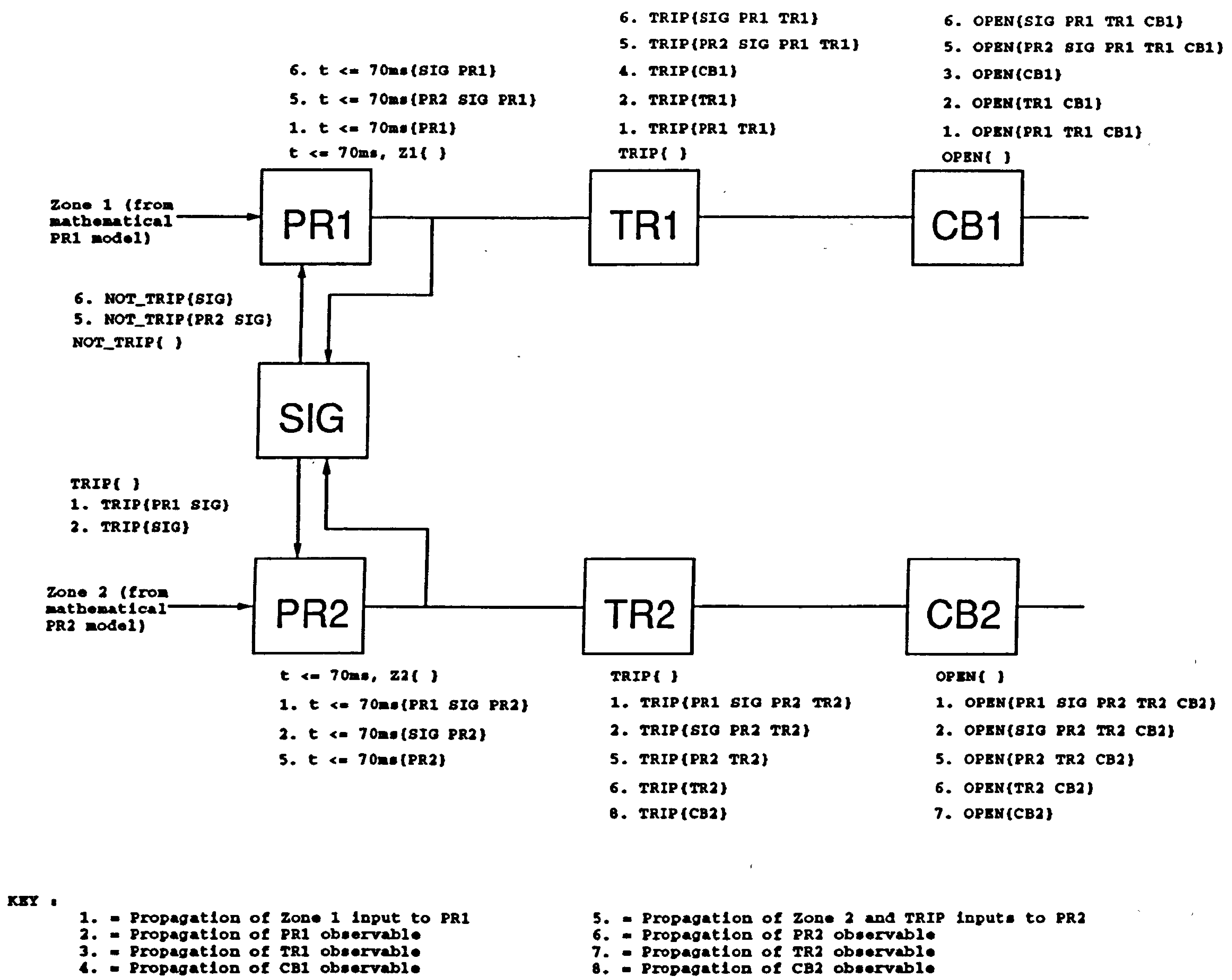


Figure 4.26: Consistency based validation of permissive under-reach distance protection scheme.

A number of inconsistencies occur when the observables are propagated throughout the model (figure 4.27). From these the resulting conflict sets are as listed in table 4.25.

<PR1 SIG PR2>
<SIG PR2>
<PR2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR2 TR2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR2 TR2 CB2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR2 TR2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR2 TR2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR2 TR2 CB2>

Table 4.25

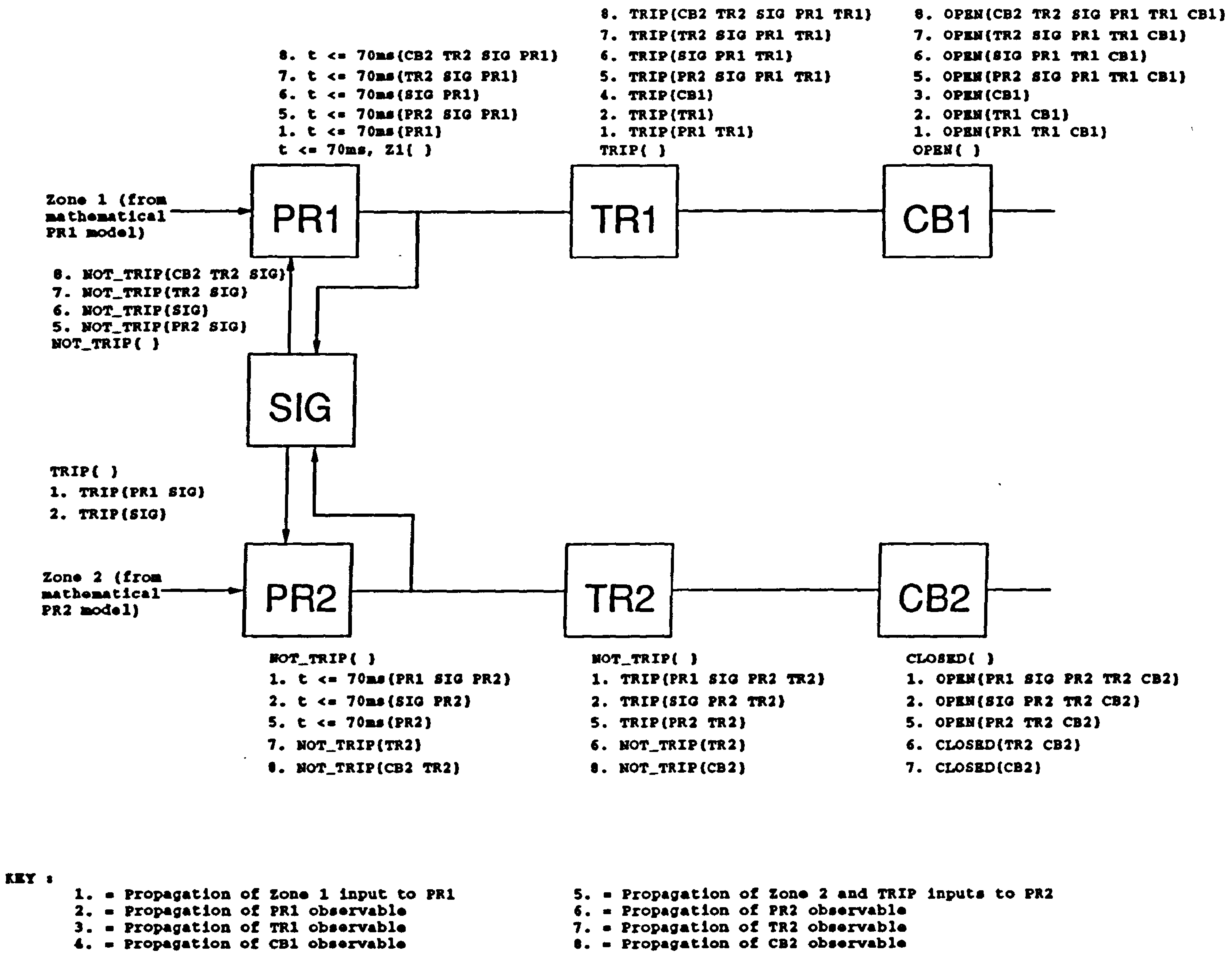


Figure 4.27: Consistency based diagnosis of permissive under-reach distance protection scheme : Example 1

In fact, these are all duplicates or supersets of <PR2> which results in the candidate set being [PR2]. Therefore, the hypothesis is that PR2 has malfunctioned with the model predicting that it should have operated within 70ms.

This example is now repeated with the exception of the observable at the signalling input to each protection relay. In this case the assumption is that the output from the signalling channel is not visible. This affects propagation from the zone two operation of PR2. As the signalling input is unknown then the operational time of PR2 is unable to be determined from known inputs. The other observables can be used as before (figure 4.28).

The conflict sets generated are shown in table 4.26.

<PR1 SIG PR2>
<SIG PR2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR1 SIG PR2 TR2>
<SIG PR2 TR2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>

Table 4.26

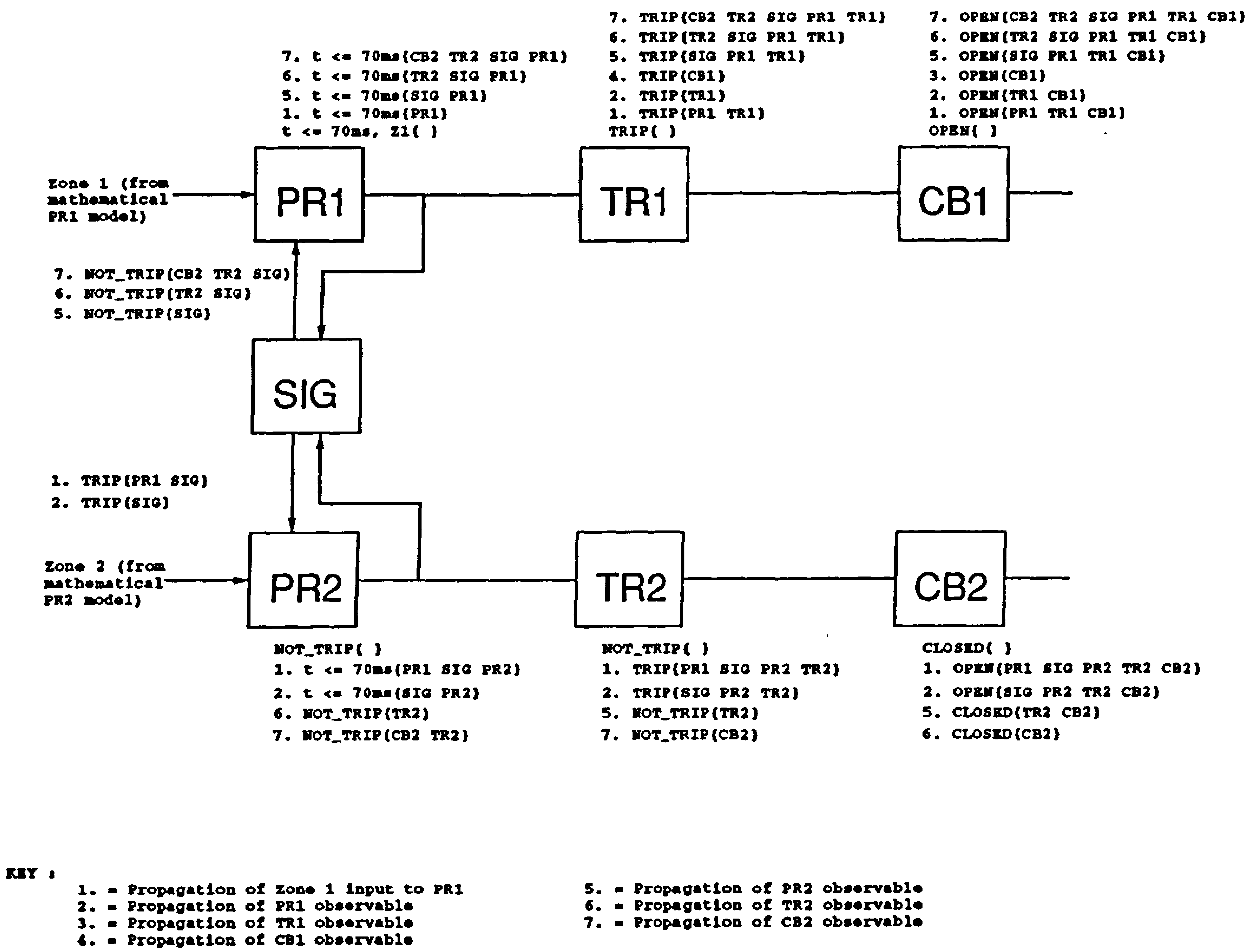


Figure 4.28: Consistency based diagnosis of permissive under-reach distance protection scheme : Example 2 (using a decreased number of observables).

These are all supersets of <SIG PR2>. Two candidate sets arise :

[SIG] [PR2]

Table 4.27

The hypotheses in this case show that if the output from the signalling channel is not visible then it is impossible to determine whether the protection relay or the signalling system failed. Once more the robustness of consistency based diagnosis under limited data conditions is shown. In this instance the diagnosis is not incorrect or incomplete, merely it is impossible to narrow the possibilities further given this data input.

A final diagnostic example considers the case where CB2 fails. This scenario would give rise to the following observables (assuming the output from SIG is not visible) :

PR1 operation	= $\text{time}_{TRIP} \leq 70$ ms, zone 1
TR1 status	= TRIP
CB1 status	= OPEN
PR2 operation	= $\text{time}_{TRIP} \leq 70$ ms, zone 2
TR2 status	= TRIP
CB2 status	= CLOSED

Table 4.28

Eleven conflict sets are produced from discrepancies arising from the propagation process (figure 4.29). These are given in table 4.29.

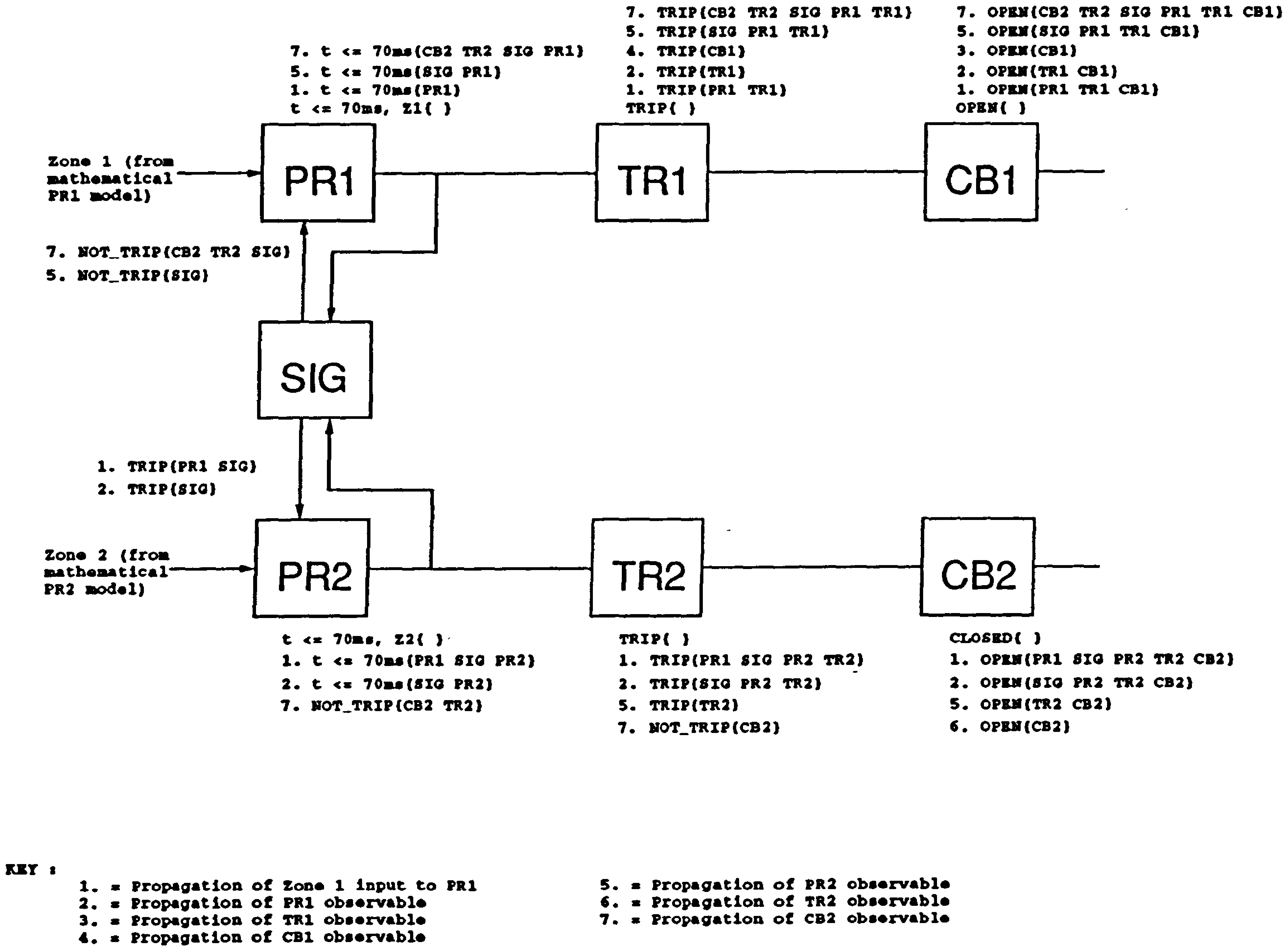


Figure 4.29: Consistency based diagnosis of permissive under-reach distance protection scheme : Example 3

<TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<TR2 CB2>
<PR1 SIG PR2 TR2 CB2>
<SIG PR2 TR2 CB2>
<TR2 CB2>
<CB2>

Table 4.29

These are all duplicates or supersets of <CB2>, hence [CB2] becomes the candidate set indicating failure of this device.

In this example, the reduced set of observables does not cause any uncertainties in the diagnosis. This is because PR1 and PR2, which use the missing observables, operate as their models predict for the zone 1 and zone 2 faults detected.

4.5.4 Consistency based diagnosis of an overcurrent protection scheme

The consistency based diagnostic methodology can cope with models of an equational nature. In the case of the non-unit Inverse Definite Minimum Time (IDMT) overcurrent protection scheme, a series of time and current graded protection relays are utilised (figure 4.30). The time of protection operation is governed by a set of characteristic equations. Each protection relay has settings applied to it, to define the required operating time. These settings are the plug setting and time multiplier setting. In addition, the current transformer ratio and nominal relay rating are used.

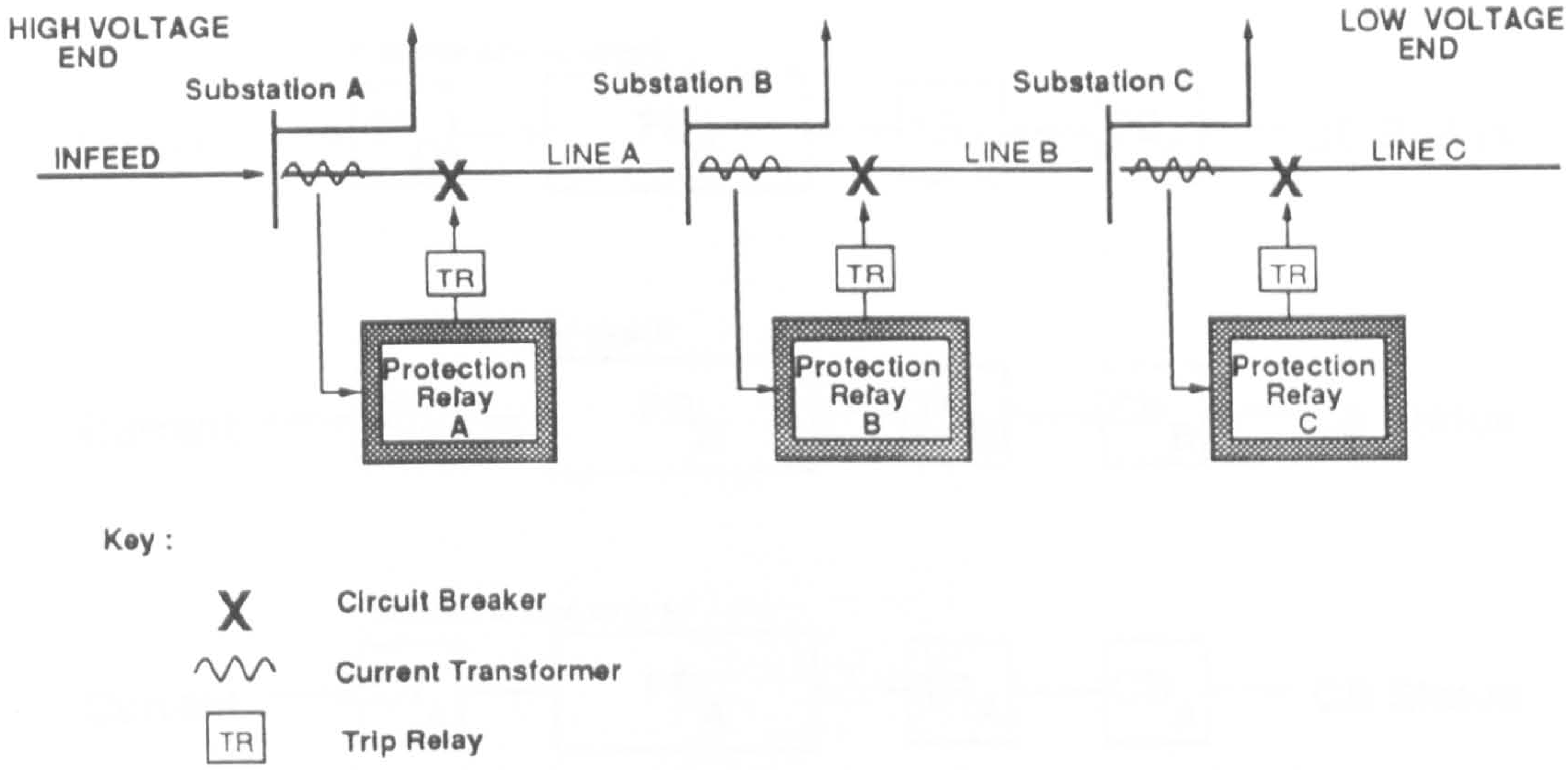


Figure 4.30: IDMT overcurrent protection scheme.

The mathematical equations for (standard) IDMT protection are :

$$PSM = \frac{Current}{PS \times CT\ ratio \times relay\ rating}$$

$$time_{characteristic} = \frac{0.14}{PSM^{0.02} - 1}$$

$$time_{actual} = time_{characteristic} \times TMS$$

where, *PSM* is the plug setting multiplier, *PS* is the plug setting and *TMS* is the time multiplier setting.

In figure 4.31, the protection relay would be modelled with the given equations. The settings for each relay are shown in table 4.30 and the rating of all the relays is 5A.

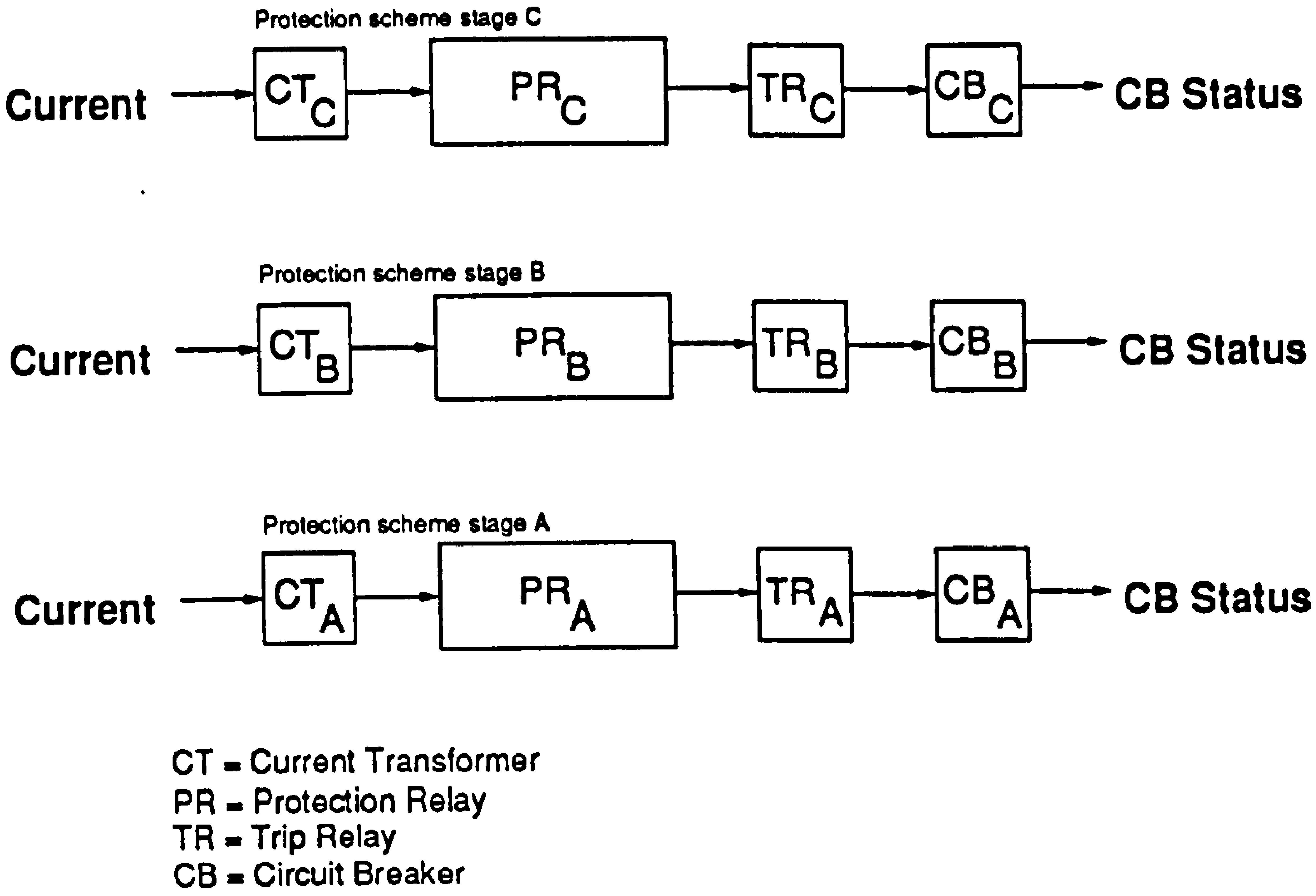


Figure 4.31: Model of IDMT non-unit protection.

Protection Relay	Plug Setting	Time Multiplier Setting	CT Ratio
A	50%	0.1	200/5
B	50%	0.27	300/5
C	100%	0.37	300/5

Table 4.30

To allow the protection relay to be used to calculate the input current from a known operating time ($time_{actual}$) the characteristic equations are rearranged thus :

$$
\begin{aligned}
time_{characteristic} &= \frac{time_{actual}}{TMS} \\
PSM &= \exp\left(\frac{\ln\left(\frac{0.14}{time_{characteristic}} + 1 \right)}{0.02} \right) \\
Current &= PSM \times PS \times CT\,ratio \times relay\,rating
\end{aligned}
$$

Thus, bidirectionality of the protection relay model is achieved through both sets of equations.

The observables are assumed to be the current, the protection relay operating time plus trip relay and circuit breaker status (derived from fault records and SCADA system data). Therefore, the models of the other components are as shown in figure 4.32.

CT

Input	Output
X	X

TR

Input	Output
Trip	Trip
Not_Trip	Not_Trip

CB

Input	Output
Trip	Open
Not_Trip	Closed

Figure 4.32: Component models for IDMT overcurrent protection scheme.

Within the scheme protection relays A and B offer backup for protection relay C. Also, protection relay A offers backup functionality for protection B. For this protection scheme each stage (i.e. as shown in figure 4.31) operates independently. If the fault is cleared before a protection relay reaches its operating time then it will not trip. For the example diagnoses it is assumed that data is available which indicates the faulted feeder. This could be derived from fault records, or from the conclusions produced by the knowledge based module of the DSS. From this and circuit breaker statuses the stages of the protection scheme which should operate can be determined, indicating those which the consistency based diagnostic process should be applied to. A diagrammatic representation of this strategy is shown in figure 4.33.

It is assumed that the fault current can be obtained from fault records with the trip relay and circuit breaker statuses being available from fault records or SCADA system data. The first case to be considered is a fault on line C as a result of which the observations shown in table 4.31 were made.

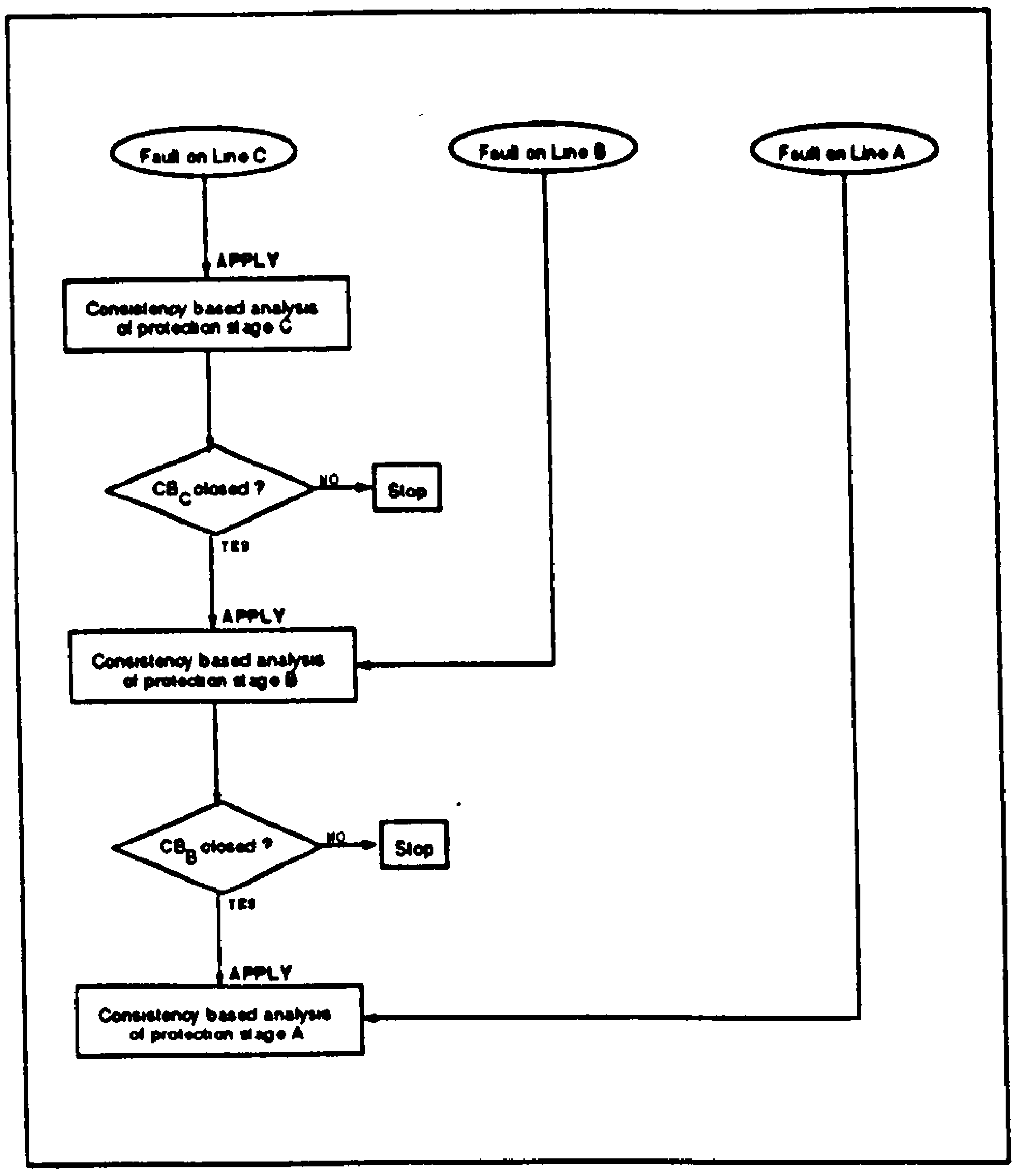


Figure 4.33: Diagnostic strategy for IDMT protection scheme.

I_{FAULT} = 1925A
PR_C operating time = 0.23s
TR_C status = TRIP
CB_C status = OPEN

Table 4.31

These are propagated (according to the diagnostic strategy in figure 4.33) as demonstrated in figure 4.34. As a result of the models used the protection relay operating time can not be derived from the trip relay or circuit breaker status. After propagation of the observables no discrepancies are evident, allowing a tolerance of ± 1% for analogue values. Therefore, the protection performance has been validated.

The second diagnostic example once more assumes a fault on line C with the observables being as indicated in table 4.32.

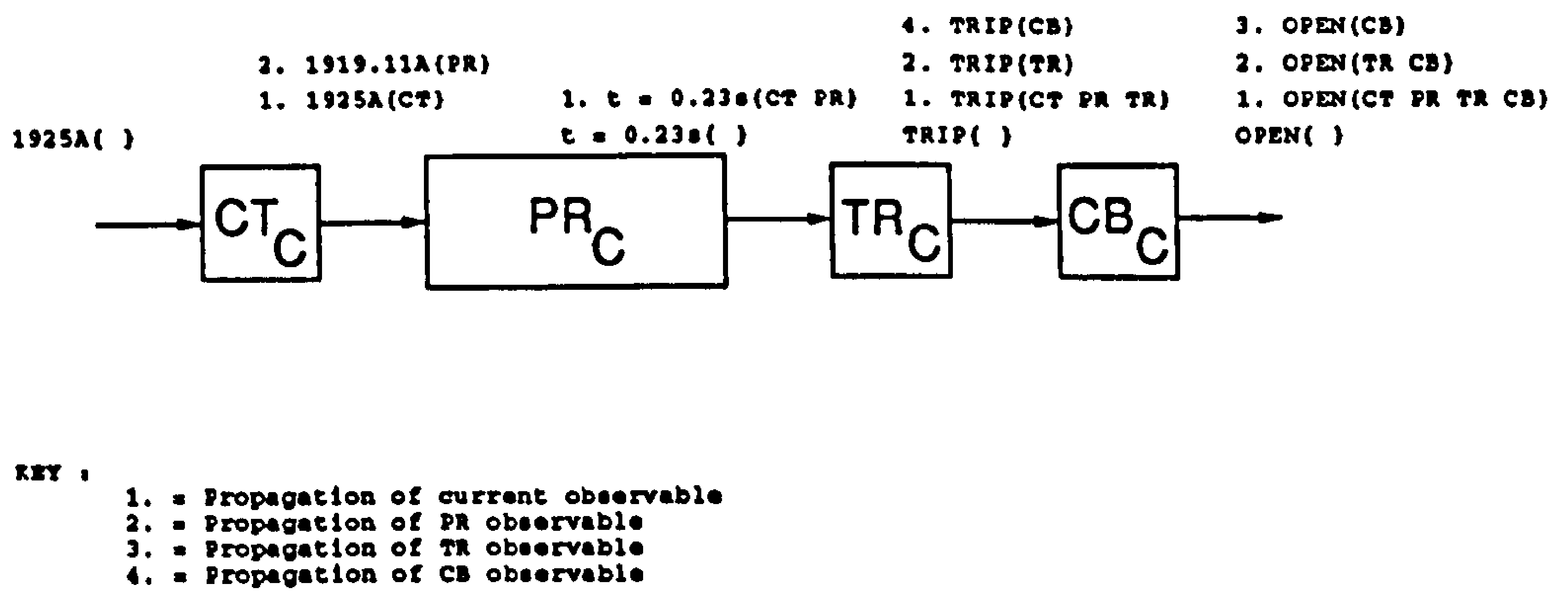


Figure 4.34: Consistency based validation of IDMT protection scheme.

I_{FAULT}	= 1925A
PR_C status	= NOT_TRIP
TR_C status	= NOT_TRIP
CB_C status	= CLOSED
PR_B operating time	= 0.72s
TR_B status	= TRIP
CB_B status	= OPEN

Table 4.32

Based on the diagnostic strategy (figure 4.33) these values are propagated as presented in figure 4.35.

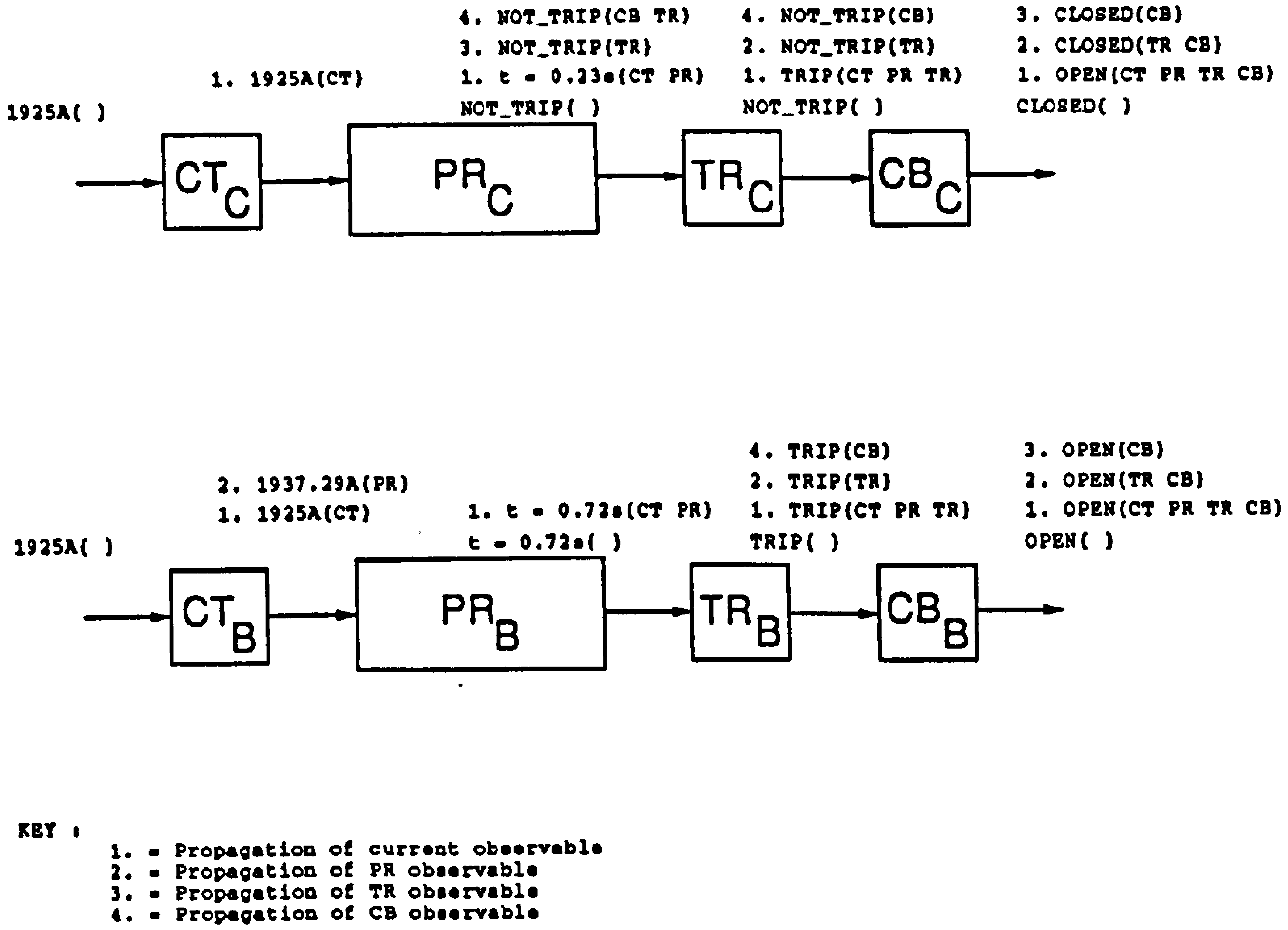


Figure 4.35: Consistency based diagnosis of IDMT protection scheme.

Table 4.33 shows the conflict sets which arise for protection stage C.

$< CT_C\ PR_C >$
$< CT_C\ PR_C\ TR_C >$
$< CT_C\ PR_C\ TR_C\ CB_C >$

Table 4.33

Therefore, the minimal conflict set is $< CT_C\ PR_C >$. Either the current transformer or the protection relay has failed. Discrimination between the two could have been achieved if the exact current measured by the current transformer was available. Practically, this is impossible since the exact measurement taken by the protection current transformer is not known. If it had been available, and the measurement was the same as the fault recorder current, then the current transformer would have been exonerated, and the diagnosis would have been that the protection relay failed, since a single candidate set would have been produced.

The operation of protection stage B has been validated as no discrepancies occur (once more allowing a tolerance of ± 1 % for analogue values). The overall conclusion is that PR_C should have operated in 0.23s but failed so PR_B operated as backup to clear the fault.

4.6 Assessment of consistency based diagnosis for power system protection

As stated previously, the case studies of consistency based diagnosis applied to varying protection schemes were intended as a feasibility study of a novel application of MBD. In each case the protection performance was validated or appropriate diagnoses were generated. The importance of these example diagnoses is that complete sets of possible single and multiple device malfunctions, explaining the observed values, were generated without fault models or heuristic diagnostic knowledge. If a knowledge based approach was used each variation of input and output possibilities would require to be enumerated, with the appropriate diagnoses detailed. Therefore, the model based approach is more practicable as it requires a single model of correct behaviour to diagnose all scenarios. Additionally, it is more robust as knowledge bases generally cover faults experienced, therefore novel events are not catered for. Nevertheless, it was identified that fault models and knowledge based techniques would be more appropriate for discrimination between possible hypotheses when assessing the performance of power system protection. Importantly, the benefits of this diagnostic approach are dependent on the quality and accuracy of the protection models employed.

When using consistency based validation and diagnosis the protection scheme model is completely independent of the reasoning engine, permitting separation into two distinct modules: the reasoning engine and a model library. This means that the reasoning strategy need not be altered to accommodate new models, as long as the models are in the required form. Therefore, it facilitates the application of the diagnosis to different protection schemes. This aids the maintainability of the diagnostic system as model updates do not affect the reasoning engine. The model library would be composed of a number of varying model types (e.g. logical, mathematical, etc.) for different devices. The scheme model will then be a hybrid of the most appropriate component models, which will be completely transparent to the consistency based diagnosis algorithm. Importantly, this methodology readily supports hierarchical models where a component indicated as malfunctioning can then be represented by models of its sub-components and a more detailed diagnosis performed.

Due to the independent nature of the protection model library, reuse of the models is facilitated for other applications such as power system analysis or simulation. Alternatively, the MBD approach could make use of existing models designed for applications other than the analysis of power system protection performance.

In terms of related research, there have been a number of systems reported which tackle the problem of automatically processing the data stored by digital fault recorders. The AFRA (Automatic Fault Record Analysis) system uses heuristics to determine the type of fault and whether the protection operation was slow or not [46]. A similar system has been reported by Kezunovic et al. [47], which uses a rulebased system in conjunction with signal processing software to try and determine when protection has failed or operated falsely. Wiot et al. report on a three level approach to digital fault record analysis [48]. Their system firstly determines the faulted feeder, phases and fault distance. Following from this, the second level module performs a knowledge based post-mortem analysis to verify protection and breaker operation.

The third level module collates statistics on fault types, fault positions, fault current,etc.

These systems all tackle the validation of protection functionality by using high level heuristics. After extracting the actual analogue values which the protection relay experiences, these systems still seem to perform a lot of qualitative based analyses. Therefore, they cannot offer the detail of diagnosis or validation that a consistency based approach, in conjunction with accurate models of protection, is able to. Furthermore, these systems seem to be restricted to static knowledge models of protection operation. The approach discussed in this chapter allows models of the dynamic behaviour of protection schemes to be considered, once more adding to the detail of diagnosis and validation possible. However, the three systems discussed have a lot to offer. This is not just in terms of protection engineer utilisation, but they could be used to feed appropriate data to the DSS being considered in this thesis, and in particular they could provide the observables used within the consistency based validation and diagnostic process.

4.6.1 Experience of Implementation

A prototype MBD system was implemented using Prolog. This had two diagnostic engines : one based on constraint suspension and the other based on the GDE diagnostic approach. Earlier models of unit, distance and IDMT protection were implemented.

The prototype showed the constraint suspension approach to be less efficient as it effectively re-runs the model for every fault candidate. When the models are not computationally intensive (due to a small number of components or a simple qualitative representation) the difference would not be significant. However, if complex models were being used then the time taken to reach a diagnosis increases combinatorially. The GDE based approach is more economical in that it runs the model once from each observable. The ATMS then deals with the discrepancies and environments produced.

Experience of the prototype and of using the diagnostic methodology is being used to construct an on-line MBD system. In tandem, the library of protection models is being extended through research. These specify protection scheme operation with detailed temporal models of behaviour. This complicates the diagnostic process as different devices within a protection scheme operate with different timescales (e.g. a protection relay, trip relay and circuit breaker have different operating times). Therefore, discrepancies must be collated within an appropriate timeframe. For example, once the protection relay operates one would not expect instantaneous operation of the trip relay, but it should operate after a certain time period. To allow for this, the concept of "episodes" (time intervals where consistency can be matched) are being investigated for implementation within an on-line MBD system.

A practical problem when implementing the on-line MBD system is that, despite increasing implementation of fault recording equipment, there is not a full coverage of fault recorder data. Therefore, the on-line system will be designed to extract information from SCADA system data in the absence of fault records. For example, the timing of protection operations, circuit breaker movement, etc. could be derived from alarms. This will affect the models which can be used (as they may need to be more qualitative in nature) and the tolerances and accuracies required in the diagnostic process, which will reflect the accuracy of the SCADA system data.

4.7 Chapter Summary

This chapter discussed the area known as model based diagnosis, highlighting key research which has been reported for this domain, and its application to the validation and diagnosis of power system protection performance. Consistency based diagnosis has been proposed as an appropriate technique to adopt. It has been shown that appropriate protection models can be generated which the consistency based diagnostic approach can make effective use of. This was demonstrated through a number of case studies assessing the feasibility of applying this technique within the DSS. It was concluded that consistency based diagnosis is suited to the comprehensive validation and diagnosis of power system protection performance, and the future benefits of adopting this technique were highlighted.

Chapter 5

Integration of the Modules within the Decision Support System

5.1 Chapter Overview

Through the previous chapters of this thesis the requirement for an improved data interpretation tool for protection engineers has been identified. A DSS comprising two modules has been proposed : knowledge based interpretation of SCADA system data; model based validation and diagnosis of protection performance. The functionality of the modules has been dealt with in detail in previous chapters. This chapter considers their integration and interaction when interpreting data during a power system disturbance. As a result, a reasoning control module is proposed, which would manage the interaction. Having identified the integration strategy required to develop the complete DSS, its benefits, utilisation and future possibilities are considered.

5.2 Integration of the KBS and MBD Modules within the Decision Support System

When considering the implementation of the DSS being proposed, a significant issue is that of integrating the two modules it comprises of. In order to integrate the two modules effectively, the interaction between them must be understood. Therefore, a case study of a possible interpretation, as performed by the complete DSS, is presented through which the required interaction between the modules will be characterised. The conceptual architecture of the DSS was shown in figure 3.3.

5.2.1 Case study of complete DSS interpretation

This case study is intended to demonstrate the interaction between the knowledge based and model based modules within the DSS. Figure 5.1 shows the pertinent power system network and protection schemes. Both feeders have distance protection relays configured to offer a permissive under-reach transfer trip scheme.

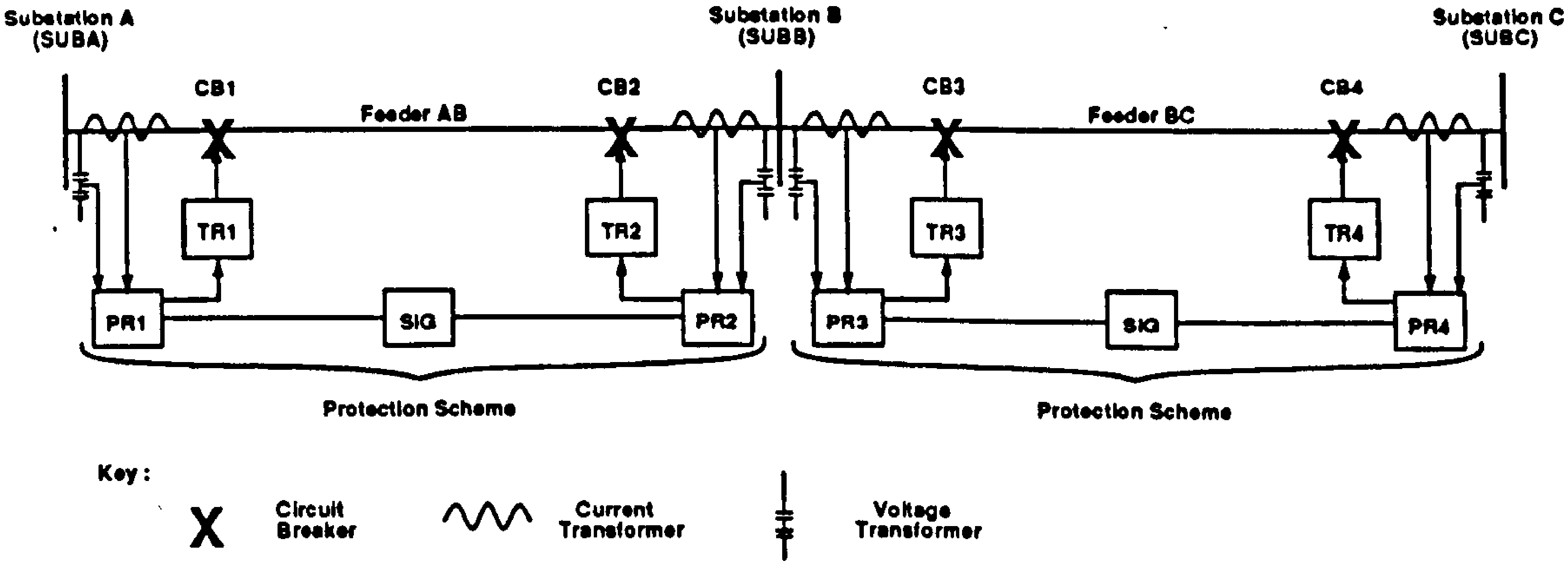


Figure 5.1: Power system network for case study of integrated DSS.

5.2.1.1 Knowledge based module

The initial raw data processed is SCADA system alarms. Those received were :

07:08:14.85	SUBA	SUBB	MAIN PROTECTION OPTD	ON
07:08:14.86	SUBA	SUBB	TRIP RELAYS TO BE RESET-E	ON
07:08:14.91	SUBA	CB1	OPEN CLOSED	OPEN
07:08:15.45	SUBC	SUBB	MAIN PROTECTION OPTD	ON
07:08:15.51	SUBC	CB4	OPEN CLOSED	OPEN
07:08:14.95	SUBA	SUBB	MAIN PROTECTION OPTD	OFF
07:08:15.46	SUBC	SUBB	TRIP RELAYS TO BE RESET-E	ON
07:08:24.86	SUBA	SUBB	TRIP RELAYS TO BE RESET-E	OFF
07:08:15.55	SUBC	SUBB	MAIN PROTECTION OPTD	OFF
07:08:24.56	SUBC	SUBB	TRIP RELAYS TO BE RESET-E	OFF

Table 5.1

In response to this, APEX generates the following conclusions (using the rulebase given in Appendix B) :

```
07:08:14.85
SUCCESSFUL PROTECTION OPERATION AT SUBA (SUBB)

07:08:14.86
TRIP RELAYS RESET AT SUBA (SUBB)

07:08:15.45
SUCCESSFUL PROTECTION OPERATION AT SUBC (SUBB)

07:08:15.46
TRIP RELAYS RESET AT SUBC (SUBB)

Event initiated at 07:08:14.91 at SUBA
Not all expected messages were received: Possible solution
(SUBA (SUBB)) ISOLATED
The message SUBB CB2 OPEN was expected but was not received.

Event initiated at 07:08:15.51 at SUBC
Not all expected messages were received: Possible solution
(SUBC (SUBB)) ISOLATED
The message SUBB CB3 OPEN was expected but was not received.
```

Table 5.2

As discussed in Chapter 3 and Appendix A, the nature of APEX is that it should give an indication of the events taking place as promptly as possible. Hence, its knowledge is shallow in terms of protection models. APEX has no concept of backup protection operation and thus expects both circuit breakers on each feeder to open.

Although this is a limitation (by design) of APEX, it does not detract from its usefulness. It still identifies key events of interest to the protection engineers. The more detailed knowledge within RESPONDD compensates for APEX under such circumstances. RESPONDD's diagnostic output is shown in table 5.3.

There was an earth or phase fault on SUBA to SUBB: feeder AB which is temporary or permanent which the protection equipment isolerate.

Table 5.3

As there is no autoswitching configured, RESPONDD cannot determine whether the fault is permanent or temporary. This would be the top ranking hypothesis, based on the internal measure of relative likelihood used by the KBS. The hypotheses considered by RESPONDD, in order of decreasing relative likelihood, are given in table 5.4.

Fault on feeder AB, PR2 failed
Fault on feeder BC, PR3 failed
Fault on feeder AB, PR2 alarm missing, TR2 failed
Fault on feeder BC, PR3 alarm missing, TR3 failed
Fault on feeder AB, PR2 alarm missing, TR2 alarm missing, CB3 failed
⋮
Fault on feeder AB and feeder BC, PR2 and PR3 failed
⋮

Table 5.4

The conclusions are generated on-line by both APEX and RESPONDD. Hence, as a disturbance occurs and the SCADA system data arrives, the DSS provides information, regarding the events, as soon as is possible. Unfortunately, SCADA system data is not sufficient to determine what happened in any greater detail.

Clarification of the actual fault(s) can be achieved through usage of the detailed data available from fault records. This data is used for model based validation of the protection operations. Within the DSS, the knowledge based module should select the protections which it considers necessary to validate. In this case it seems that PR2 at SUBA could have failed, therefore the knowledge based module would initiate an analysis of the fault records pertinent to this protection scheme. For completeness, it could also validate the other protection which operated (PR4 at SUBC). These requests would be passed to the model based module which would initiate automatic dial-up of the appropriate fault recording equipment. If APEX and RESPONDD do not indicate any protection failures or maloperations, then the DSS could be designed to suggest validation of the protection operations. This would be to confirm that the required fault clearance times were being achieved.

5.2.1.2 Model based module

The permissive under-reach scheme is modelled as shown in figure 5.2, the same model being applied to both feeders (i.e. for feeder AB : x=1 and y=2, for feeder BC : x=3 and y=4).

As in Chapter 4, section 4.5.3, the protection relay model includes the calculation of the fault zone from the three phase voltages and currents. However, this is omitted from this discussion for clarity, and only the subsequent *logical* decisions within the model are considered. The component models are shown in figure 5.3.

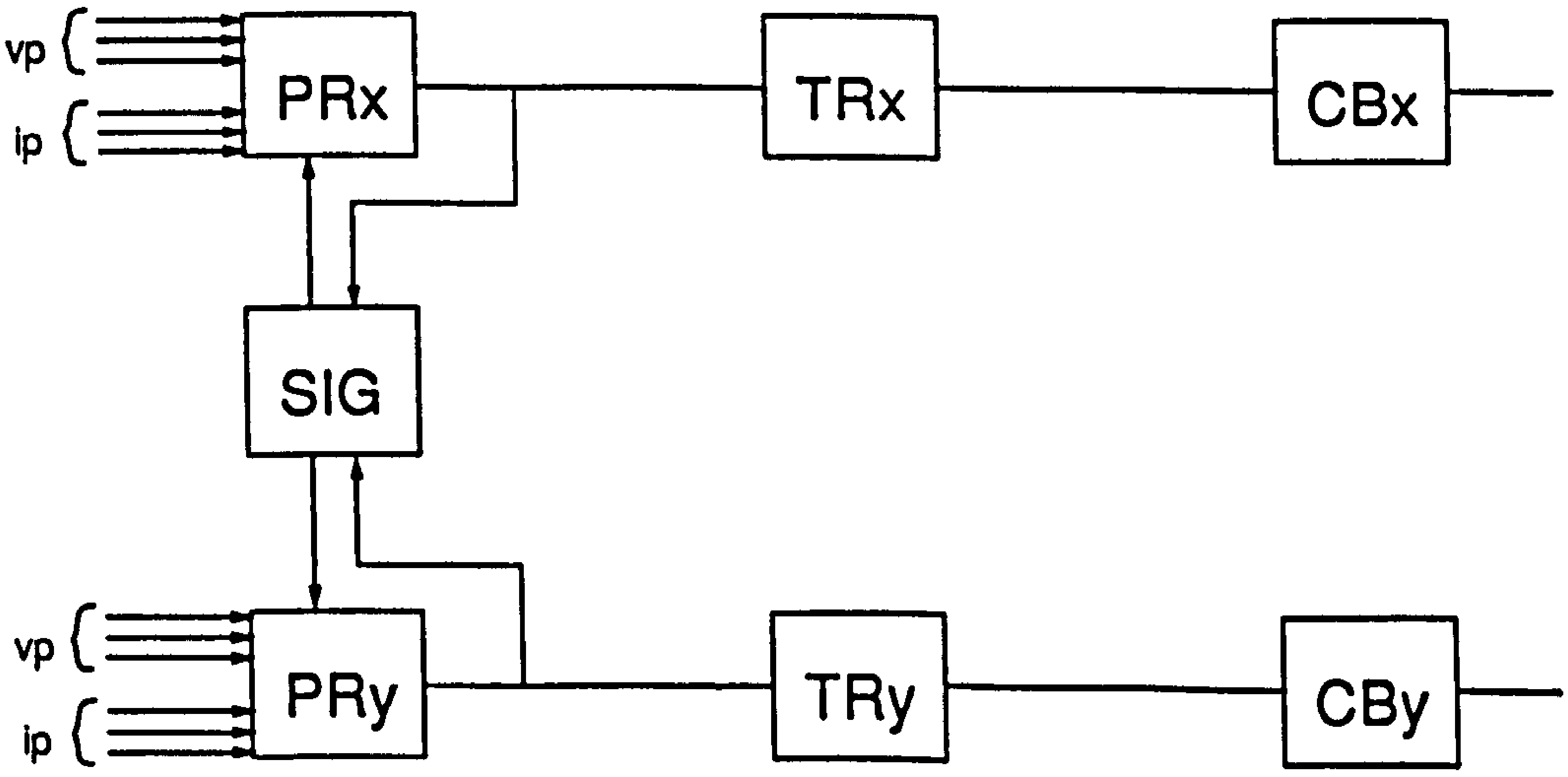
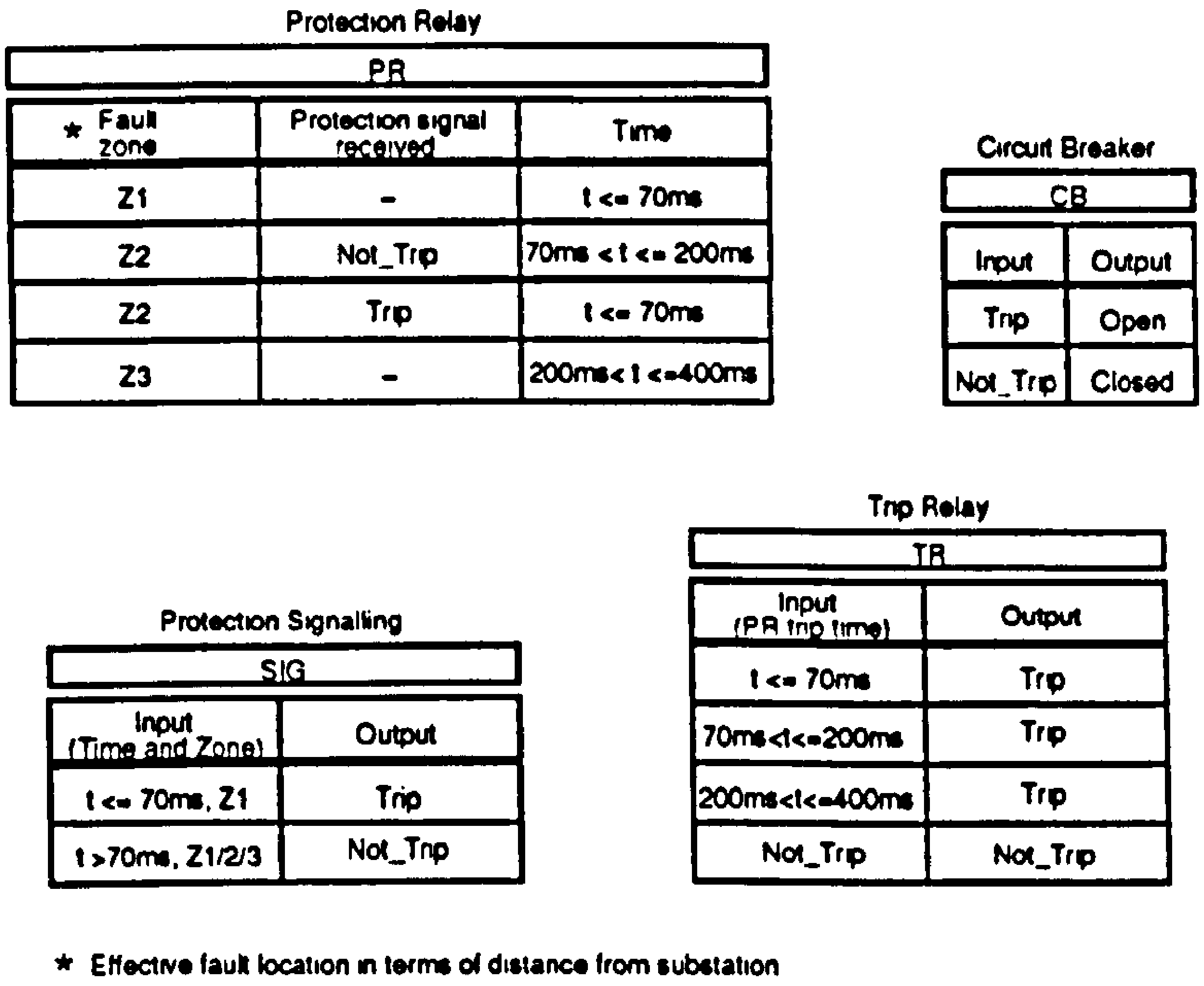


Figure 5.2: Model of permissive under-reach distance protection scheme.



Protection Relay

PR

* Fault zone	Protection signal received	Time
Z1	-	t <= 70ms
Z2	Not_Trip	70ms < t <= 200ms
Z2	Trip	t <= 70ms
Z3	-	200ms< t <=400ms

Circuit Breaker

CB

Input	Output
Trip	Open
Not_Trip	Closed

Protection Signalling

SIG

Input (Time and Zone)	Output
t <= 70ms, Z1	Trip
t >70ms, Z1/2/3	Not_Trip

Trip Relay

TR

Input (PR trip time)	Output
t <= 70ms	Trip
70ms<t<=200ms	Trip
200ms<t<=400ms	Trip
Not_Trip	Not_Trip

* Effective fault location in terms of distance from substation

Figure 5.3: Component models for permissive under-reach distance protection scheme.

The observables shown in table 5.5 are assumed to be derived from the fault records accessed by the DSS.

PR1 operation = $\text{time}_{TRIP} \leq 70$ ms, zone 1
SIG input to PR1 = NOT_TRIP
TR1 status = TRIP
CB1 status = OPEN

PR2 operation = NOT_TRIP
SIG input to PR2 = TRIP
TR2 status = NOT_TRIP
CB2 status = CLOSED

Table 5.5

These values are propagated throughout the model as shown in figure 5.4.

From the conflict sets generated, only one minimal conflict set arises : <PR2>. This means that the candidate set is [PR2]. Hence, the consistency based diagnostic process has validated protection PR1's operation and indicated that PR2 maloperated. Additionally, figure 5.4 shows that PR2 was expected to operate in under 70ms.

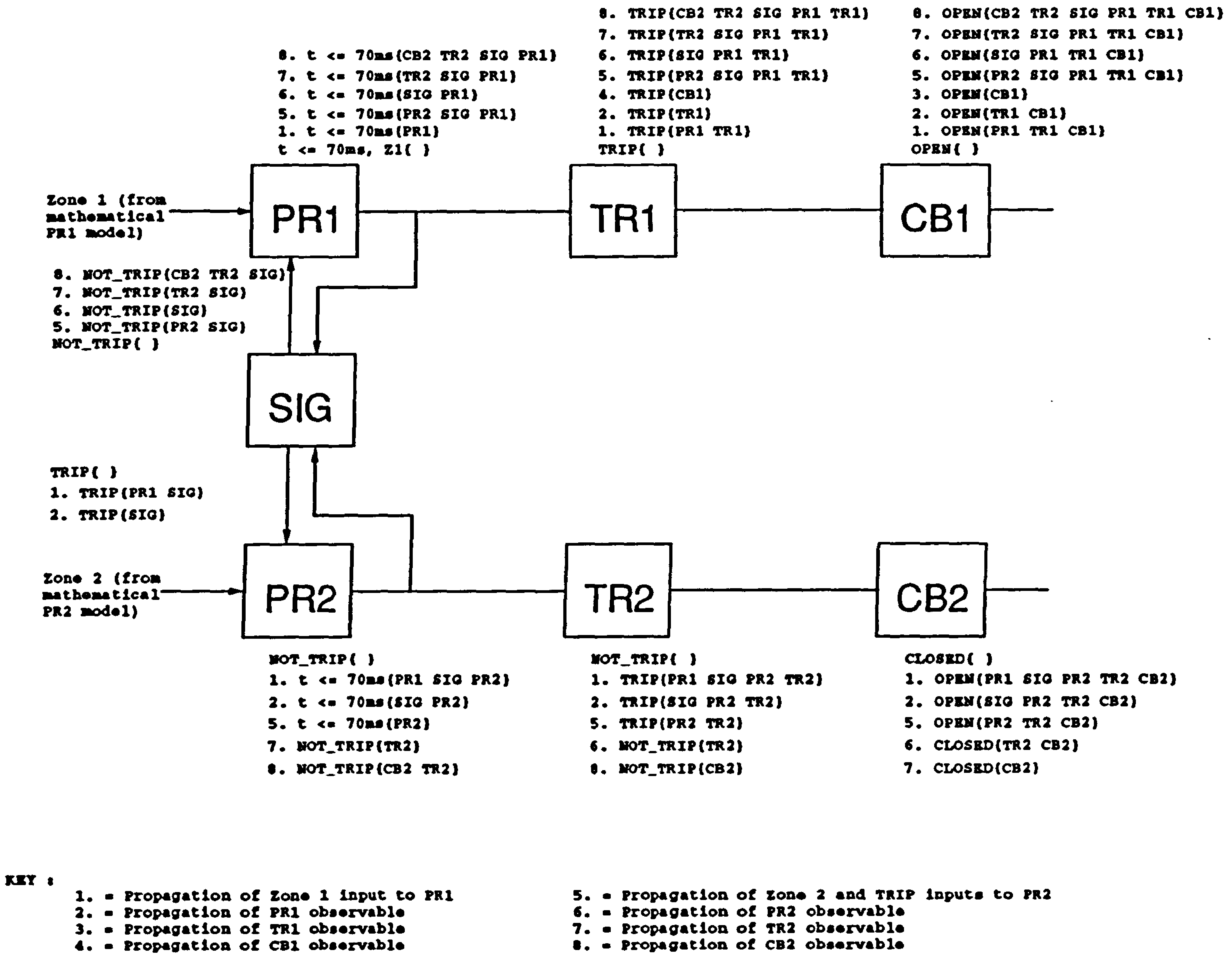


Figure 5.4: Diagnosis of the protection scheme on feeder AB.

Feeder BC is now investigated. Table 5.6 contains the relevant observables (again, from the fault records accessed).

PR3 operation = NOT_TRIP
SIG input to PR3 = NOT_TRIP
TR3 status = NOT_TRIP
CB3 status = CLOSED

PR4 operation = 200 ms $< \text{time}_{TRIP} \leq$ 400 ms, zone 3
SIG input to PR4 = NOT_TRIP
TR4 status = TRIP
CB4 status = OPEN

Table 5.6

These values are propagated throughout the model (figure 5.5). No discrepancies arise, hence this protection operation has been validated. So, PR4 operated in zone 3 to clear a fault.

The results of the MBD analysis of both protection schemes support the conclusion reported by RESPONDD. At this point a complete interpretation of SCADA system data and the relevant fault records has been achieved.

5.2.2 Discussion of case study

The case study covered the interaction between the three intelligent systems contained within the two modules of the DSS. Each one interpreted data from the same disturbance. APEX highlighted some of the key events of interest to the protection engineers. RESPONDD provided a disturbance overview and the model based module validated and diagnosed the relevant protection schemes, as directed by the knowledge based module.

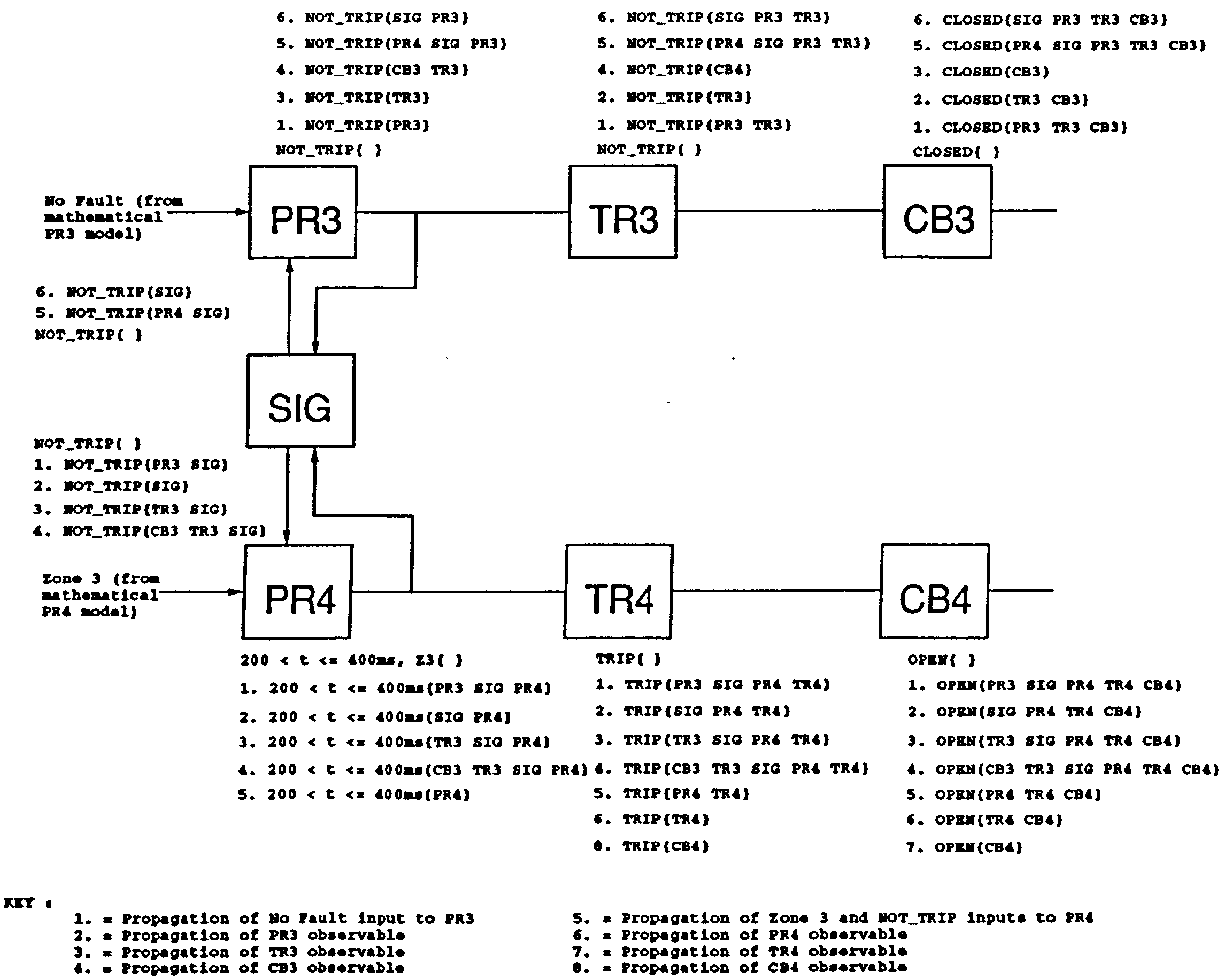


Figure 5.5: Validation of the protection scheme on feeder BC.

For this disturbance, RESPONDD produced a number of ranked hypotheses based on the SCADA system data received. The first two were :

1. Fault on feeder AB, PR2 failed
2. Fault on feeder BC, PR3 failed

Table 5.7

Hypothesis 1 was output by RESPONDD in the first instance. Model based interpretation of the fault records supported this conclusion. Nevertheless, the DSS must be able to update previous conclusions based upon improved data and more detailed reasoning. Therefore, if the model based module indicated that protection PR1 operated in zone 3 within 400ms, PR4 operated in zone 1 within 70ms and PR3 failed then the DSS should indicate that RESPONDD conclusion 2 was actually the correct hypothesis. In summary, RESPONDD suffers from there being limited information content within SCADA system data, along with poor time stamping and communication failures. Only by supporting RESPONDD with the MBD module can the situation be clarified.

So far, the interpretation of data during an ongoing disturbance has been discussed. However, once the MBD validations or diagnoses are complete, three separate interpretations of the disturbance exist. APEX and RESPONDD produce conclusions dealing with the SCADA system data received, whereas the MBD system deals with fault records. These could be combined into an overall disturbance analysis which can be used by the protection engineers and archived for future reference.

If the hypotheses produced by APEX are considered, two of these indicate that feeders have been isolated and expected circuit breaker activity is missing. RESPONDD and the MBD system's analysis do not indicate that the circuit breakers should have opened. Hence, this aspect of the APEX conclusions can be ignored. Nevertheless, the two conclusions can be combined to provide an indication that both feeders AB and BC were isolated during this disturbance.

In addition to the above, RESPONDD pinpointed the faulted area of the network as being feeder AB, which is the most significant piece of information it provides.

In summary of the model based validation of the protection performance, it demonstrates that PR1 operated correctly in zone 1 within 70ms but PR2 failed to operate (it was expected to trip within 70ms). As a result, PR4 operated in zone 3 and within 400ms.

The above summary conclusions need to be combined into an overall disturbance report. An example is given below :

> DISTURBANCE AT 07:08:14.85
>
> Feeders AB and BC were isolated due to the opening of CB1 at SUBA and CB4 at SUBC.
>
> All alarms were received for main protection and trip relay operations related to SUBA PR1 and SUBC PR4.
>
> There was an earth or phase fault on feeder AB (which is temporary or permanent) which protection PR1 at SUBA operated in Zone 1 within 70ms to clear. PR2 at SUBB should have tripped, under permissive under-reach conditions, to clear the fault within 70ms, but failed to operate. As a result PR4 at SUBC tripped in zone 3 to clear the fault within 400ms.

Table 5.8

This is a complete disturbance analysis appropriate for protection engineers. The actual timing of all the device operations could be included for completeness.

To combine the outputs of the three data interpretation systems there is implicit knowledge, about their interaction, used. This could be represented within some knowledge base to create an intelligent task to combine the conclusions of the interpretation systems.

5.3 Proposed Architecture of the Integrated DSS

From the previous discussions three key tasks can be identified which any integration architecture must cater for :

- The selection of protection operations to validate and fault records to retrieve based on the SCADA system data interpretation of the knowledge based module.
- The updating of RESPONDD's disturbance overviews based on the model based protection performance analysis.
- The intelligent combination of the outputs from APEX, RESPONDD and the model based system into a single disturbance analysis report for archival purposes.

It is proposed that a *reasoning control module* is required to perform these tasks. The algorithms, intelligent or procedural, underpinning all of these tasks require further research effort to completely define the operational functionality of the reasoning control module. This extends beyond the research reported in this thesis, and requires a representative selection of scenarios, which could occur, to be studied in detail. From this the correct algorithms and/or underlying knowledge would be extracted. The concept of a reasoning control module is shown diagrammatically in figure 5.6. This is the proposed architecture to realise the conceptual system shown in figure 3.3.

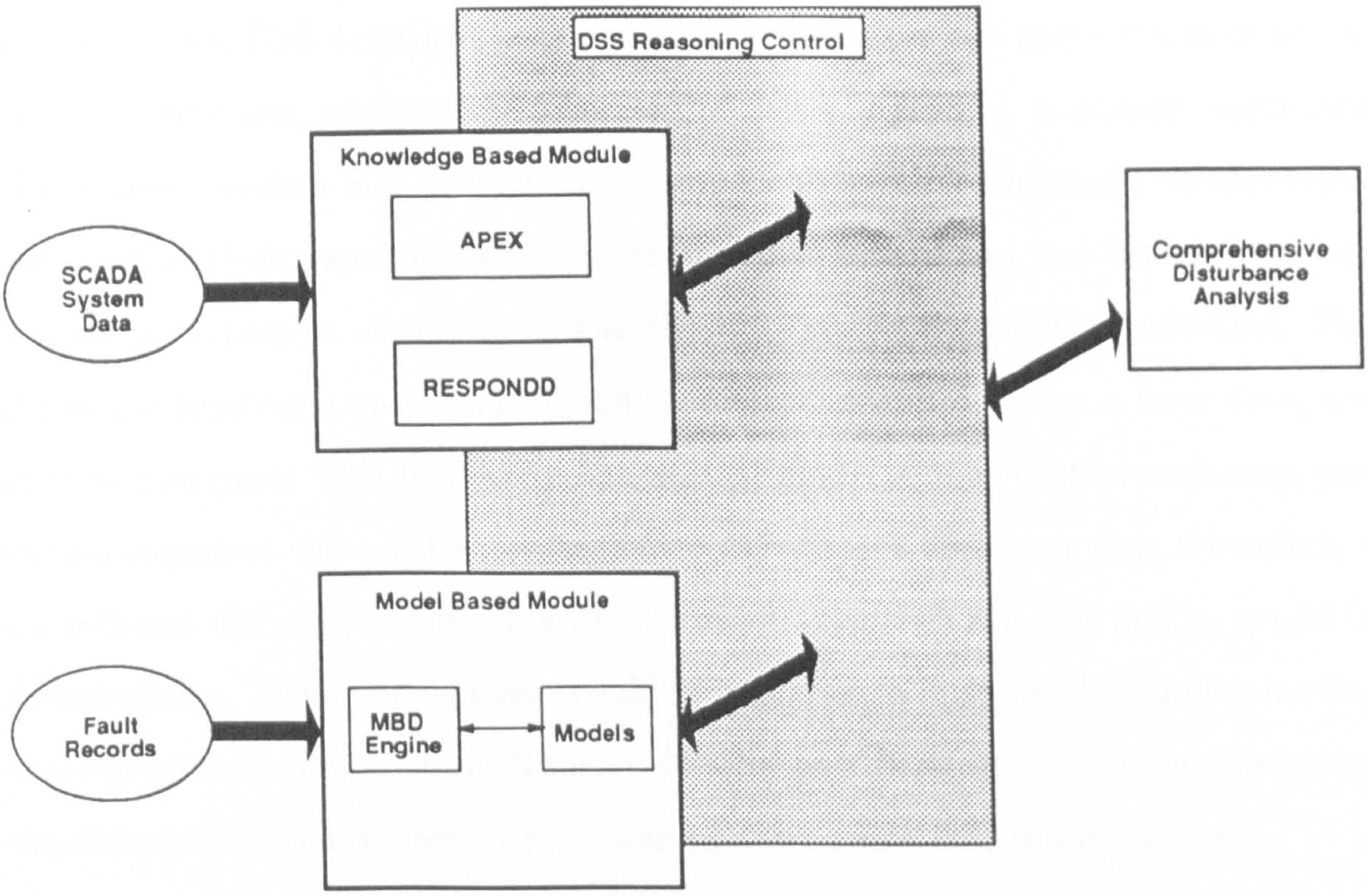


Figure 5.6: Proposed DSS architecture with a reasoning control module.

Given that this is a framework for combining multiple reasoning paradigms, it is a move towards second generation expert systems [13]. Furthermore, this concept is being taken a step further at the Centre for Electrical Power Engineering within the University of Strathclyde (Glasgow, U.K.) by a research initiative to develop *second generation reasoning systems* (SGRS). A SGRS uses multiple intelligent and algorithmic techniques to provide a suite of applications within a particular domain. For example, alarm processing, fault diagnosis, system restoration, plant monitoring and maintenance scheduling could be within a SGRS for power system control and operation. Multiparadigmed systems have complex control and communication requirements. Frameworks for their implementation them have been researched, such as the ARCHON (ARchitecture for Cooperative Heterogeneous ON-line systems) architecture for cooperating "intelligent agents" [49]. An intelligent agent is a task specific intelligent system.

5.4 Utilisation of the Integrated DSS

The integrated DSS described in this chapter would have two main modes of operation. The first one, which is the focus of the thesis in general, is on-line monitoring of the power system and protection system for protection engineers. It also offers post-fault analysis capabilities. Archived SCADA system data and fault records can be used to "replay" a disturbance, whereby the data is reinjected into the DSS. This allows the protection engineers to study a disturbance in detail at a later date, and at their own pace. This is a useful operational mode. Unlike control engineers, protection engineers will not be in attendance twenty-four hours per day. Therefore, if a significant disturbance occurs in their absence then such a replay facility would be advantageous. The archived event could be replayed to improve their understanding of the events which took place. If such a detailed post-fault analysis was not necessary the disturbance analysis report produced by the on-line DSS would suffice.

At the time of writing this thesis a prototype DSS, which comprises the knowledge based module only, is operational at ScottishPower's Corporate Headquarters. It is used by two protection engineers. APEX processes SCADA system data from over one hundred substations and RESPONDD has been tuned for twelve feeders, covering twelve substations. Experience with the prototype is driving further research. To improve the presentation and assimilation of the information provided by the DSS, it is connected to a single line diagram of the power system network. This is active and reflects the present status of the switchgear within the power system.

The engineers using the DSS do so periodically, or when a significant disturbance has occurred. The DSS interprets the SCADA system data on-line as it arrives. An electronic report is produced for each conclusion and archived. In this way, the engineers have access to all the results of the knowledge based interpretation of SCADA system data. The on-line prototype is essential in that it provides both the research team and the engineers with experience of using such an intelligent system. Furthermore, it is the ideal mechanism for validating the knowledge within the DSS.

Through experience with the prototype system, future operational modes have been identified. The first of these is its use for engineer training. The DSS need not be used solely for diagnostic purposes, but could be used for training and updating engineers. By using the models resident within the DSS, the power system's behaviour during various faults could be simulated and so provide a scenario playing environment for training. This would require changes to the operation of the DSS, but the underlying models and framework to implement it reside within the system already. This is an example of knowledge and model reuse.

A second possibility for the future is the addressing of strategic management issues through the DSS. It can provide information relating to the maloperation or failure of protection devices and switchgear. Furthermore, statistics concerning the frequency of failures and frequency of switchgear activity could be compiled automatically by the DSS. Such information can be used to schedule maintenance procedures. In fact, this is a move towards performance based maintenance, as scheduling would be based on the actual health of the devices. Further research is required in this area.

The compiling of fault and failure statistics is required for annual reports within the utility. Hence, any statistics compiled by the DSS reduce the workload of engineers tasked to provide such information.

5.5 Chapter Summary

This chapter discussed the issue of integrating the knowledge based and model based modules of the DSS. The interaction between them was highlighted through a case study of a disturbance analysis. Consideration was given to the knowledge based module focusing the validation of the model based module. Furthermore, the output of the MBD system can be used to update or improve the hypotheses generated by the KBS interpretation of SCADA system data. Finally, the outputs of the three intelligent systems within the DSS can be combined into a comprehensive disturbance report. From these considerations, the functions required to be performed by a reasoning control module were identified. However, further research is required before a full specification of its functionality is possible.

The utilisation of such a DSS was considered. On-line monitoring and post-fault analysis are immediate requirements which can be fulfilled. Additionally, training, maintenance scheduling and statistics compilation for internal reports may all be facilitated by the DSS in the future.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The research presented within this thesis concerns the data analysis problems of protection engineers, and their alleviation through the use of intelligent systems. An underlying theme has been the extraction of information from data.

It was identified that the three main aspects of protection engineers' data analysis were as follows :

- Identification of the key events indicated by SCADA system data.
- Generation of an overview of any disturbance, based on SCADA system data.
- Comprehensive validation of protection performance, using the detailed data available from fault records or equivalent.

In order to facilitate these tasks, a decision support system was proposed. This interprets both SCADA system data and fault records to provide an analysis of protection performance. Interpretation of SCADA system data is achieved through knowledge based systems technology. The knowledge based module comprises two on-line intelligent systems which offer the following benefits :

- Summarisation of incoming alarms into discrete events of interest.
- Identification of isolated plant within the power system network.
- Indication of the reconnection of isolated areas of the power system network.
- Provision of fault diagnostic information, which offers a disturbance overview.
- Identification of "missing" events, which point to further required analyses.

The information from the knowledge based module is provided on-line and replaces the requirement for time consuming manual analysis of SCADA system data. Therefore, protection engineers are alerted to potential problems, such as protection failures, sooner than is possible if manual data analysis is required. This is most beneficial during storm conditions or major disturbances where the volume of SCADA system data generated can be overwhelming. In some instances this can take several weeks to analyse. In summary, on-line data rationalisation, through interpretation, is provided by the knowledge based module. Intelligent alarm interpretation tends to be targeted at control centres. However, this research has shown the requirement for distributing such techniques to facilitate other tasks within utilities.

Although KBS interpretation of SCADA system data offers effective data analysis support for protection engineers, it suffers from the fact that there is limited information contained within such data. Furthermore, SCADA systems experience telecommunication problems and failures. As a result, comprehensive validation of protection performance requires fault records or equivalent data from modern microprocessor based protection relays (with inbuilt data storage capabilities). The second module of the DSS will interpret such detailed data.

A form of model based diagnosis, known as consistency based diagnosis, has been proposed as an appropriate method of validating protection performance, and highlighting failures. Traditionally, this paradigm has been applied in the realm of digital circuit diagnostics. Within this application, models of "good" protection device behaviour are used to predict expected operations, which are then compared to the actual operations which occurred (as indicated by fault records). The models can be exploited to diagnose any failures if the actual and predicted behaviours are not consistent. Consistency based diagnosis permits the use of detailed protection models which are able to employ the quantitative data available from fault records. A feasibility study of the potential use of this technique for protection validation was presented in the thesis. The conclusion drawn is that it is viable to include this paradigm within the DSS.

The benefits of adopting such a model based approach to protection performance analysis can be summarised as :

- Only a single model of correct behaviour is required, no fault models are necessary. Importantly, this means that novel faults can be diagnosed.
- The diagnostic approach can produce a complete set of possible single and multiple component failures which explain the observed operations.
- It is a robust diagnostic method. During instances of poor data availability the diagnosis will degrade gracefully.
- The diagnostic engine and models are independent. This offers a number of important advantages for the DSS :
  - A library of protection device models can be created which the diagnostic engine can interface with. This allows the most appropriate model to be chosen based upon data availability, depth of diagnosis required, etc.
  - The reuse of models is catered for, both for and from other applications.
  - Hierarchical models are supported readily. Therefore, the diagnostic process can localise a failure and then call a more detailed model of the suspected device or subsystem for further investigation.
  - A key advantage is that this independence of models and diagnostic mechanism aids the maintainability of the system.

Having considered the functions which the DSS will provide, it is essential that the two modules are integrated correctly. In the first instance, KBS interpretation of alarms will focus the attention of the MBD module. Once the detailed validation and diagnosis of protection performance has been completed, the results can be used to compensate for any uncertainty in the KBS conclusions. Following from this, a comprehensive disturbance analysis report may be produced. This research has demonstrated the requirement for a reasoning control module in order to achieve the above interactions.

Overall, the DSS will provide powerful data analysis and interpretation capabilities for protection engineers. The requirement for time consuming manual data processing will be removed, with the on-line interpretations of the DSS focussing the tasks of the protection engineers. Such a facility is becoming essential during a time when the number of protection engineers is decreasing, their responsibilities are being extended and the amount of available data is increasing rapidly.

Through the underlying models within the DSS (both knowledge models and functional models) different operational modes can be achieved. Once the complete DSS is constructed, the possible operational modes are :

- On-line monitoring of power system protection performance.
- Off-line post-fault analysis of disturbances.
- Engineer training.
- Strategic management (compilation of fault statistics, maintenance scheduling).

In terms of the contribution of this work to the research community, three aspects are considered to be significant :

- The application of intelligent data interpretation for protection engineers, and as a result furthering the concept of distributing intelligent systems throughout the electricity supply industry.

- The use of MBD for comprehensive validation and diagnosis of power system protection.
- A consideration of the issues underlying, and the requirements for, the integration and interaction of different expert system paradigms to provide comprehensive data interpretation.

6.2 Future Work

The main task which must be addressed now is to produce an on-line model based module for protection validation and diagnosis. Through utilisation of the on-line system, required extensions and improvements to the diagnostic engine will become apparent. Furthermore, the on-line system will allow investigations into interfacing models from other applications with the diagnostic engine.

The protection scheme models within this thesis use steady state values of voltage and current at the time of fault to determine the relay response. However, dynamic models have been developed for current transformers, voltage transformers, capacitor voltage transformers, relays and circuit breakers [50]. These dynamic models allow the effects of transient conditions on the protection relay input, which can cause maloperation, to be taken into account. The consistency based diagnosis system should be extended to allow integration with such dynamic models. Research activity has already caused extension of the GDE system for diagnosis of dynamic systems as detailed in chapter 6 of reference [51].

It is only when such an on-line model based module is developed that the efficiency of the overall DSS can be assessed. This will include the efficiency of the reasoning processes, as well as the implication of data access rates for SCADA systems, fault recorders and other intelligent devices or monitoring systems.

In terms of integrating the modules of the DSS, research is required to design and build a reasoning control module which will permit elegant and efficient interaction between the different tasks.

Finally, once the above issues have been addressed and the complete DSS is constructed, research concerning the wider applications of it can be initiated. As an example, the DSS could have its emphasis changed to validating designs of new protection schemes, This would entail modelling a new protection scheme or arrangement within the DSS and reinjecting the archived data from a disturbance. The performance of the new protection arrangement would then be simulated and assessed.

Appendix A

Description of APEX and RESPONDD

A.1 Discussion

This appendix describes the two knowledge based systems which have been integrated as the knowledge based module of the DSS. Both were designed as standalone expert systems but subsequent research and development has seen their integration into a single DSS module. The alarm processing function is performed by APEX (Alarm Processing EXpert system) while the fault diagnosis is provided by RESPONDD (Rulebased Expert System for POwer Network Disturbance Diagnosis).

A.2 APEX

One of the main criteria underlying an alarm processor is speed of operation, since its function is most important during critical conditions where a great volume of SCADA system data needs to be assimilated by engineers. Data rates can be in the order of thirty thousand alarms per hour during extreme conditions [7], as was experienced in 1987 by Eastern Electricity during violent storms. Under such critical conditions the alarm processor must accurately and efficiently identify the key events occurring. In order to fulfill this requirement APEX was coded in the 'C' programming language, allowing an efficient inference engine to be designed and built. The knowledge within APEX is *shallow* in nature, meaning that its understanding of the domain (power systems and power system protection) is not comprehensive in nature. APEX identifies events through a "fingerprint" held in its knowledge base, which describes the expected alarms for each event of interest. For the DSS in question the knowledge base was created through extensive knowledge elicitation with protection specialists. As discussed in Chapter 2, section 2.3.2.1, and shown in figure 2.7, a KBS has both a knowledge base and relevant data sources. APEX has two databases :

- Topology database.

  This details the connectivity of electrical plant within the power system network under study, covering generators, transformers, busbars, circuit breakers, isolators and lines.

- Comprehensive database of SCADA system alarms.

  This details all the messages which are available within the SCADA system.

The utilisation of these two data sources will become evident as the operation of APEX is explained in this section.

APEX is designed to cope with the problems inherent in dealing with SCADA system alarms: non standard data arrival rates; time skewed data; missing data.

A.2.1 Knowledge base

Within the knowledge base the event fingerprints, termed *rules*, are coded in a near natural language shell. This facilitates their maintenance and updating by engineers inexperienced in using high level programming languages (such as 'C'). As an example, consider the rule used to identify protection operation at the 275kV and 400kV voltage levels on ScottishPower's transmission network. In this case, four alarms are expected. Consider the feeder from Hunterston 400kV substation (whose code is HUER4) to Inverkip (whose code is INKI). The following alarms would be expected :

HUER4	INKI	FIRST MAIN PROT OPTD	ON
HUER4	INKI	FIRST MAIN PROT OPTD	OFF
HUER4	INKI	SECOND MAIN PROT OPTD	ON
HUER4	INKI	SECOND MAIN PROT OPTD	OFF

Table A.1

The first column indicates the substation where the alarm emanated, the second column is the circuit which the alarm is appropriate to, the third column is the textual alarm and the final column indicates status.

This could be represented in the knowledge base as an event specific rule as demonstrated in table A.2.

```
Event “Protection operated at HUNTERSTON (INVERKIP)”
Expect
{
    Alarm “HUER4   INKI   FIRST MAIN PROT OPTD    ON”
    Alarm “HUER4   INKI   FIRST MAIN PROT OPTD    OFF”
    Alarm “HUER4   INKI   SECOND MAIN PROT OPTD   ON”
    Alarm “HUER4   INKI   SECOND MAIN PROT OPTD   OFF”
}
```

Table A.2

The first line of the rule indicates the appropriate *event summary* for the expected alarms within the rule. This representation of knowledge would require one rule per possible protection operation on every possible circuit. Therefore, the rules are made generic through *wildcard* operators. The wildcard operators are :

<StationName> ⟶ a substation
<StationSet> ⟶ a set of substations
<CB> ⟶ a circuit breaker
<CBSet> ⟶ a set of circuit breakers
<BlackOut> ⟶ a blackout area (i.e. isolated plant)
<TR> ⟶ a transformer
<IS> ⟶ an isolator
<Line> ⟶ a line/cable

Table A.3

Using the wildcards permits rules within the knowledge base to be applied globally across the power system network under consideration. Therefore, the protection rule specific to the Inverkip circuit at Hunterston becomes of the form shown in table A.4.

```
Event "Protection operated at <StationName>"
Expect
{
    Alarm "FIRST MAIN PROT OPTD"    ON    <StationName>
    Alarm "FIRST MAIN PROT OPTD"    OFF   <StationName>
    Alarm "SECOND MAIN PROT OPTD"   ON    <StationName>
    Alarm "SECOND MAIN PROT OPTD"   OFF   <StationName>
}
```

Table A.4

The <StationName> wildcard ties together the substation and the circuit, which allows the above generic rule to perform the same task as the previously discussed protection rule.

In terms of the knowledge base's efficiency, the generic template approach has meant that only thirty rules are required to capture the significant events of interest to protection engineers. Having fewer rules within the knowledge base facilitates knowledge validation and maintenance.

A.2.1.1 Topology database

The topology database supports a number of wildcard operators: <StationSet>; <CBSet>; <BlackOut>. <StationSet> applies a rule not only to a particular substation but to an interconnected set of substations. This set is determined by APEX querying its topology database. Use of the topology database will be explained through consideration of the <CBSet> and <BlackOut> wildcard operators. Together, these are used within the most powerful rule type within APEX. The SCADA system for the utility in question indicates breaker activity in the following manner :

```
HUER4    X105    OPEN CLOSED        OPEN
HUER4    X105    OPEN CLOSED        CLOSED
```

Table A.5

Given this, consider the following rule :

```
Event "<BlackOut> isolated"
Expect
{
    Alarm "OPEN CLOSED"     OPEN     <CBSet>
}
```

Table A.6

The above rule is fired when any circuit breaker opens. However, the use of the <CBSet> wildcard triggers a topological search for any associated circuit breakers which would be expected to open for a power system fault that caused the initial circuit breaker to open. Take, for example, the network in figure A.1.

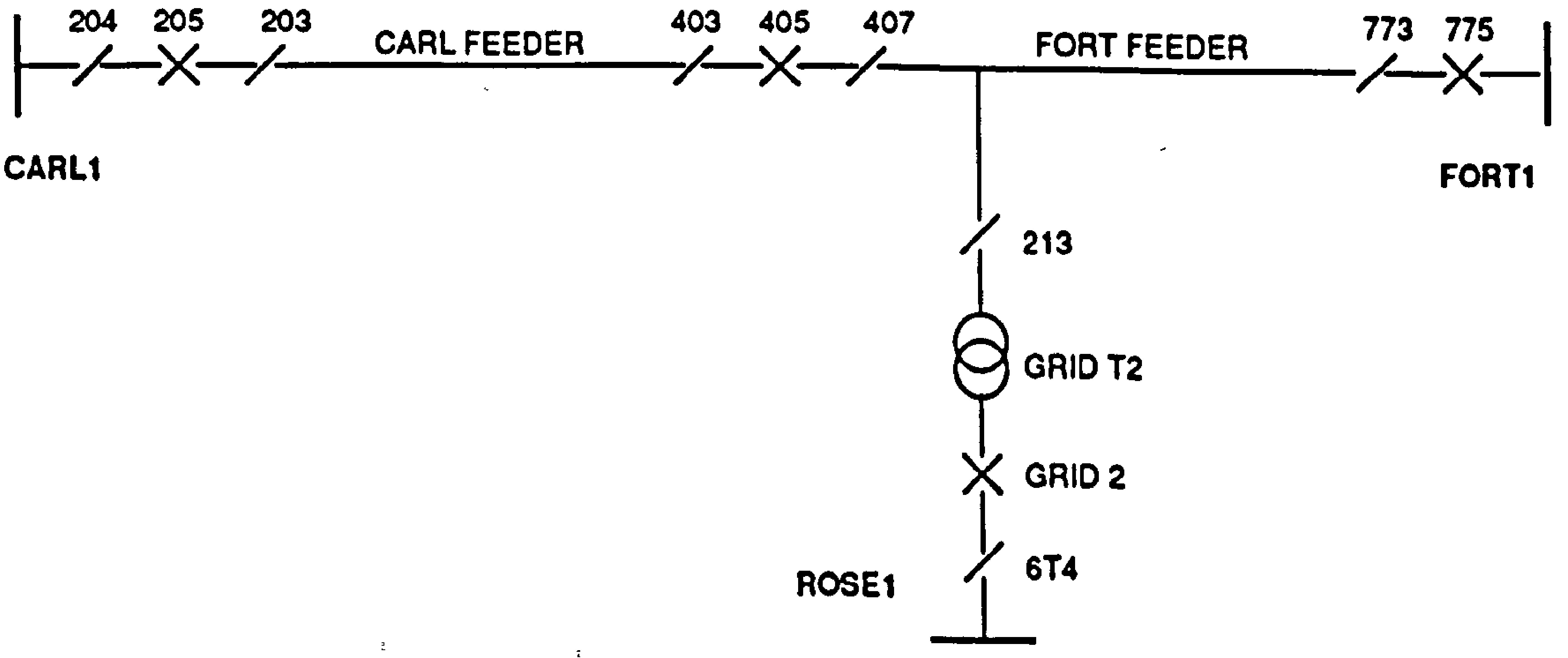


Figure A.1: Example power system network.

If 405 at ROSE1 opens, APEX finds two possible sets of circuit breakers which may open :

CBSet 1	CBSet 2
ROSE1 405 received	ROSE1 405 received
CARL1 205 expected	ROSE1 GRID2 expected
	FORT1 775 expected

Table A.7

Both of these events would be instaniated as possibilities by APEX. Once one is filled by incoming alarms, the event summary is output. At this point <BlackOut> is expanded to identify the plant bounded by the circuit breakers in each set. In this case (for figure A.1) :

CBSet1 ⟶ ROSE (CARL FEEDER) isolated
CBSet2 ⟶ ROSE (GRID T2, FORT FEEDER) isolated

Table A.8

A.2.1.2 Comprehensive database of SCADA system alarms

A database of all possible SCADA system alarms further aids the implementation of generic rules. When a rule is fired, APEX checks that all the expected alarms are valid for the circuit/substation/etc. identified through the triggering alarm. The usefulness of this feature can be explained through the following example. Interconnectors between different utilities often have more than two main protections to ensure adequate reaction to faults. Therefore, the following rule may be used :

```
Event “Protection operated at <StationName>”
Expect
{
    Alarm “FIRST MAIN PROT OPTD”     ON   <StationName>
    Alarm “FIRST MAIN PROT OPTD”     OFF  <StationName>
    Alarm “SECOND MAIN PROT OPTD”  ON   <StationName>
    Alarm “SECOND MAIN PROT OPTD”  OFF  <StationName>
    Alarm “THIRD MAIN PROT OPTD”     ON   <StationName>
    Alarm “THIRD MAIN PROT OPTD”     OFF  <StationName>
}
```

Table A.9

This rule could be applied to all 275kV and 400kV substations, which make use of the “FIRST MAIN PROT OPTD” and “SECOND MAIN PROT OPTD” alarms. These alarms cause the rule to be activated. A part of this process includes APEX cross referencing the SCADA system alarm database with the expected alarms in the rule. If any are not produced at the substation then those alarms are marked as “not expected” within the instaniated rule. For example, the following alarm is received.

HUER4	INKI	SECOND MAIN PROT OPTD	ON

Table A.10

This means that APEX checks its alarm database for the following :

HUER4	INKI	FIRST MAIN PROT OPTD	ON
HUER4	INKI	FIRST MAIN PROT OPTD	OFF
HUER4	INKI	SECOND MAIN PROT OPTD	ON
HUER4	INKI	SECOND MAIN PROT OPTD	OFF
HUER4	INKI	THIRD MAIN PROT OPTD	ON
HUER4	INKI	THIRD MAIN PROT OPTD	OFF

Table A.11

It will be found that the "THIRD MAIN PROT OPTD" alarms are not generated at Hunterston on the Inverkip circuit, therefore these are marked as not expected for the event "Protection operated at HUNTERSTON (INVERKIP)".

A.2.2 Inference Strategy

The mechanisms for instaniating rules fit into the overall inference strategy as described in this section.

When the first alarm is received by APEX it will trigger every rule within which it is an expected message. These competing events are stored within a single *hypothesis group* since they are all attempting to explain the same alarm. Any subsequent messages are compared with the expected alarms of the currently instantiated hypotheses. If there are any matches then these event hypotheses are updated to reflect the fact that an expected message had been received. Failing to match with a currently active hypothesis causes the knowledge base to be accessed, leading to the triggering of new event hypotheses if the alarm matches their template. This is termed incremental reasoning since each alarm is processed immediately and the reasoning process updated appropriately.

If all the expected messages within a rule are received then that particular event summary is output with the competing hypothesis in the same group being destroyed. However, to allow for missing telemetry and device failures, not all expected alarms need be received. Each group of hypotheses has a time out period allotted. When this period elapses, if no hypothesis has received all its expected alarms, the one which received the most is output with an indication of those alarms which did not arrive. The competing hypotheses are also retained for the users' benefit. It should be noted that the alarms need not be received in the order indicated within the rules, causing data skew to be less problematic for the alarm processor. The hypotheses can be prioritised, which allows the interpreted conclusions to be filtered if necessary.

A flowchart of this inference strategy is shown in figure A.2 (taken from [52]).

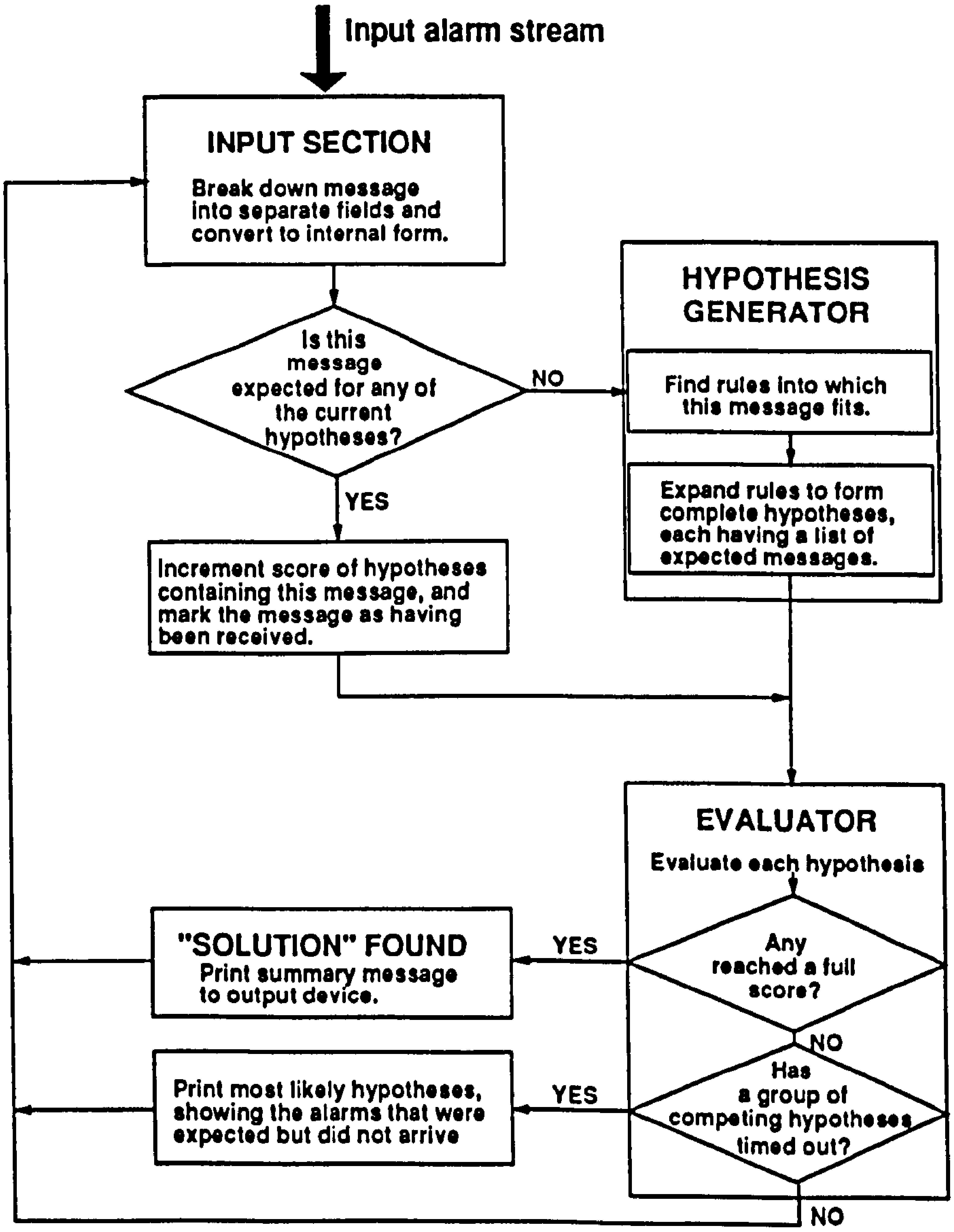


Figure A.2: Flowchart of APEX's inference strategy.

A.3 RESPONDD

RESPONDD, the fault diagnosis expert system, attempts to describe the overall power system disturbance based on received SCADA system data. It consolidates the event summaries produced by APEX.

RESPONDD provides a "deeper" (i.e. more detailed) level of reasoning than APEX, thus its knowledge base is more comprehensive. The core of RESPONDD's reasoning is based around knowledge of protection functionality. Qualitative models of protection schemes are used to simulate power system faults, leading to a scenario based generate and test approach to diagnosis. A two tiered diagnostic strategy is adopted comprising *gut reaction* followed by the *central diagnosis*. The detailed reasoning of RESPONDD is supported by more comprehensive domain data than APEX uses. For example, data regarding the power system topology includes current transformer and voltage transformer locations which is used in conjunction with the protection models. RESPONDD is coded in the Quintus Prolog (*Pro*gramming in *log*ic) language which offered the facilities to perform the required diagnostic tasks [8] [33].

During the research behind RESPONDD comparable systems were surveyed to determine any issues which were not being sufficiently addressed in this area. An extensive discussion of these systems can be found in the PhD Thesis by G.M. Burt [8].

A.3.1 Diagnostic strategy

As previously described, RESPONDD has a two stage diagnostic strategy :

- Gut reaction.

- Central diagnosis.

A.3.1.1 Gut reaction

The gut reaction module performs high level analyses of the incoming alarms. A decision is made on whether the present alarm is a control action, related to an existing hypothesis under consideration or indicative of a new scenario to be considered. If the alarm is deemed to be relevant to a new scenario then a *disturbance area* is created, which is the topological region where the primary system fault could be located. This area is determined through rudimentary models of possible fault radii. For example, the gut reaction rules know that for distance protection operation the power system fault can be up to a distance of three lines away. Since each alarm is considered as it arrives, and affects the reasoning accordingly, this is once more an example of incremental reasoning.

A.3.1.2 Central diagnosis

This module is where the core diagnostic process takes place. It is designed to consider system faults, protection and switchgear maloperations as well as telemetry problems. The main knowledge used by the central diagnosis is qualitative models of protection schemes. To demonstrate this, RESPONDD's model of differential circulating current unit protection can be thought of as a Prolog implementation of the schematic shown in figure A.3.

The current transformers are used as location identifiers for the protection scheme. The operation of each component within the protection model is indicated through SCADA system messages. When any of the devices operate the qualitative protection

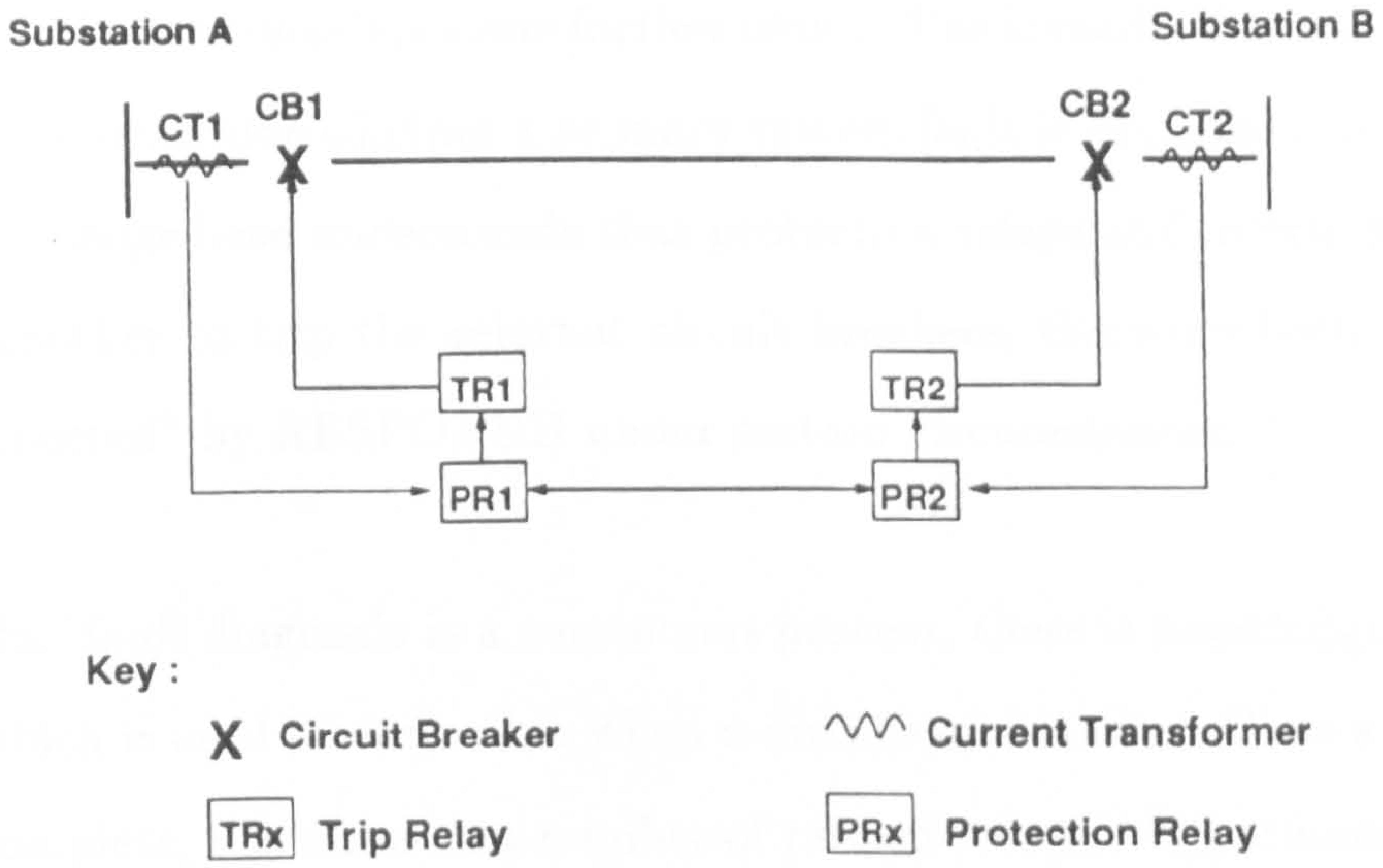


Figure A.3: Schematic of RESPONDD's unit protection model.

model allows the expected consequent operations to be inferred. This means that if TR1 is seen to operate, PR1, PR2 and TR2 would be expected to operate with CB1 and CB2 opening. Furthermore, there is knowledge associated with each type of protection regarding the generic type of faults it can react to (phase or earth) and their locations. Once a decision is made on the possible type and location of the power system fault, it is simulated qualitatively (the simulation is qualitative due to the lack of good quality on-line measurements available from most SCADA systems) [8]. The fault is assumed to exist and all possible protection reactions are simulated. This will provide the expected activity in terms of protection relays, trip relays, circuit breakers and intertrips. The simulated activity is then compared with the incoming alarms.

Obviously, the case where everything operates correctly is covered by this process. However, false operations of devices, maloperations and telemetry failures are all considered and produce competing scenario hypotheses. If device maloperation is considered, then backup protection activity is simulated. This is where RESPONDD differs greatly from APEX in terms of its depth of interpretation. Mechanisms are included to prevent combinatorial explosion of hypotheses at this point.

RESPONDD also considers some further issues. Use is made of delayed autoreclosure activity to determine whether a primary system fault is permanent or temporary. Also, the knowledge base understands that protection relays and intertrip signals can "race" one another to trip the relevant circuit breakers, therefore both of these are "possibly expected" by RESPONDD under certain circumstances.

Given that fault diagnosis is a continuous process, there is knowledge within RESPONDD which is used to determine when a disturbance is over. Once a disturbance is deemed complete, there can be a number of ranked scenario hypotheses to describe what occurred. These are ranked according to a measure of relative likelihood, which was developed through the research into this fault diagnosis expert system. Although mathematically and statistically sound techniques exist for providing measures of uncertainty in expert systems, there are no statistics available for the probabilities of failure of protection devices, circuit breakers, telecommunication circuits, etc. Therefore, relative likelihoods are used which do not indicate definite probabilities but a subjective likelihood with respect to the other competing scenarios.

A case study of the operation of RESPONDD, in conjunction with APEX, is presented in section 3.4.2. However, the type of hypothesis presented by RESPONDD is as follows (taken from [8]):

There was a ground fault on dumb to moss:feeder 2 which is (permanent or temporary) which the protection equipment cleared.

Table A.12

Explanation of the event and reasoning is also provided by RESPONDD, an example of which is given in Table A.13.

In fact because rief2 at dumb will not isolate the fault due to the failure of cb5 at dumb to trip, rdefl at drum operated, rsbef2 at drum operated, & rsbefl at dumb operated to isolate the fault.

Table A.13

In this example, RESPONDD is describing how the failure of circuit breaker cb5 at dumb means that operation of the protection relay rief2 did not isolate the fault. As a result, the relays rdefl and rsbef2 (at drum) plus rsbefl (at dumb) operated as backup.

Appendix B

APEX Rulebase for Case Studies

```
; ------------------------------------------------
; Description of events and expected Alarm patterns
; ------------------------------------------------
; Special names:
; <CB> A circuit breaker
; <CBSet> A set of circuit breakers (1 or more CBs)
; <StationSet> A set of substations
; <StationName> A single substation
; <BlackOut> A set of blacked out network nodes
; <Line> A line/cable
; <TR> A transformer
; <IS> An isolator

; ----------------------
; Isolation and reclosure
; ----------------------


Event "<BlackOut> isolated"
Priority 25
Expect
{
    Alarm "OPEN CLOSED" OPEN <CBSet>
}

Event "<BlackOut> reclosed"
Priority 25
Expect
{
    Alarm "OPEN CLOSED" CLOSED <CBSet>
}


; ----------------------
; Protection operations
; ----------------------


Event "Successful protection operation at <StationName>"
Priority 25
Expect
{
    Alarm "FIRST MAIN PROT OPTD" ON <StationName>
    Alarm "FIRST MAIN PROT OPTD" OFF <StationName>
    Alarm "SECOND MAIN PROT OPTD" ON <StationName>
    Alarm "SECOND MAIN PROT OPTD" OFF <StationName>
}
```

```
Event "Successful protection operation at <StationName>"
Priority 25
Expect
{
    Alarm "MAIN PROTECTION OPTD" ON <StationName>
    Alarm "MAIN PROTECTION OPTD" OFF <StationName>
}


; ------------------------
; Trip relay operations
; ------------------------


Event "Trip relays reset at <StationName>"
Priority 0
Expect
{
    Alarm "TRIP RELAYS TO BE RESET-E" ON <StationName>
    Alarm "TRIP RELAYS TO BE RESET-E" OFF <StationName>
}


; ------------------------
; Intertrip operations
; ------------------------


Event "First and second intertrip received at <StationName>"
Priority 0
Expect
{
    Alarm "FIRST INTERTRIP REC OPTD" ON <StationName>
    Alarm "FIRST INTERTRIP REC OPTD" OFF <StationName>
    Alarm "SECOND INTERTRIP REC OPTD" ON <StationName>
    Alarm "SECOND INTERTRIP REC OPTD" OFF <StationName>
}

Event "Intertrip received at <StationName>"
Priority 0
Expect
{
    Alarm "INTERTRIP RECEIVE > OPTD" ON <StationName>
    Alarm "INTERTRIP RECEIVE > OPTD" OFF <StationName>
}
```

```
Event "Intertrip received at <StationName>"
Priority 0
Expect
{
    Alarm "INTERTRIP RECEIVE < OPTD" ON <StationName>
    Alarm "INTERTRIP RECEIVE < OPTD" OFF <StationName>
}

Event "Intertrip received at <StationName>"
Priority 0
Expect
{
    Alarm "INTERTRIP RECEIVE OPTD" ON <StationName>
    Alarm "INTERTRIP RECEIVE OPTD" OFF <StationName>
}


; ------------------------
; Autoswitching operations
; ------------------------


Event "Successful autoswitching sequence at <StationName>"
Priority 16
Expect
{
    Alarm "AUTO SWITCHING IN PROG" ON <StationName>
    Alarm "AUTO SWITCHING IN PROG" OFF <StationName>
    Alarm "AUTO SWITCHING COMPLETE" ON <StationName>
    Alarm "AUTO SWITCHING COMPLETE" OFF <StationName>
}
```

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