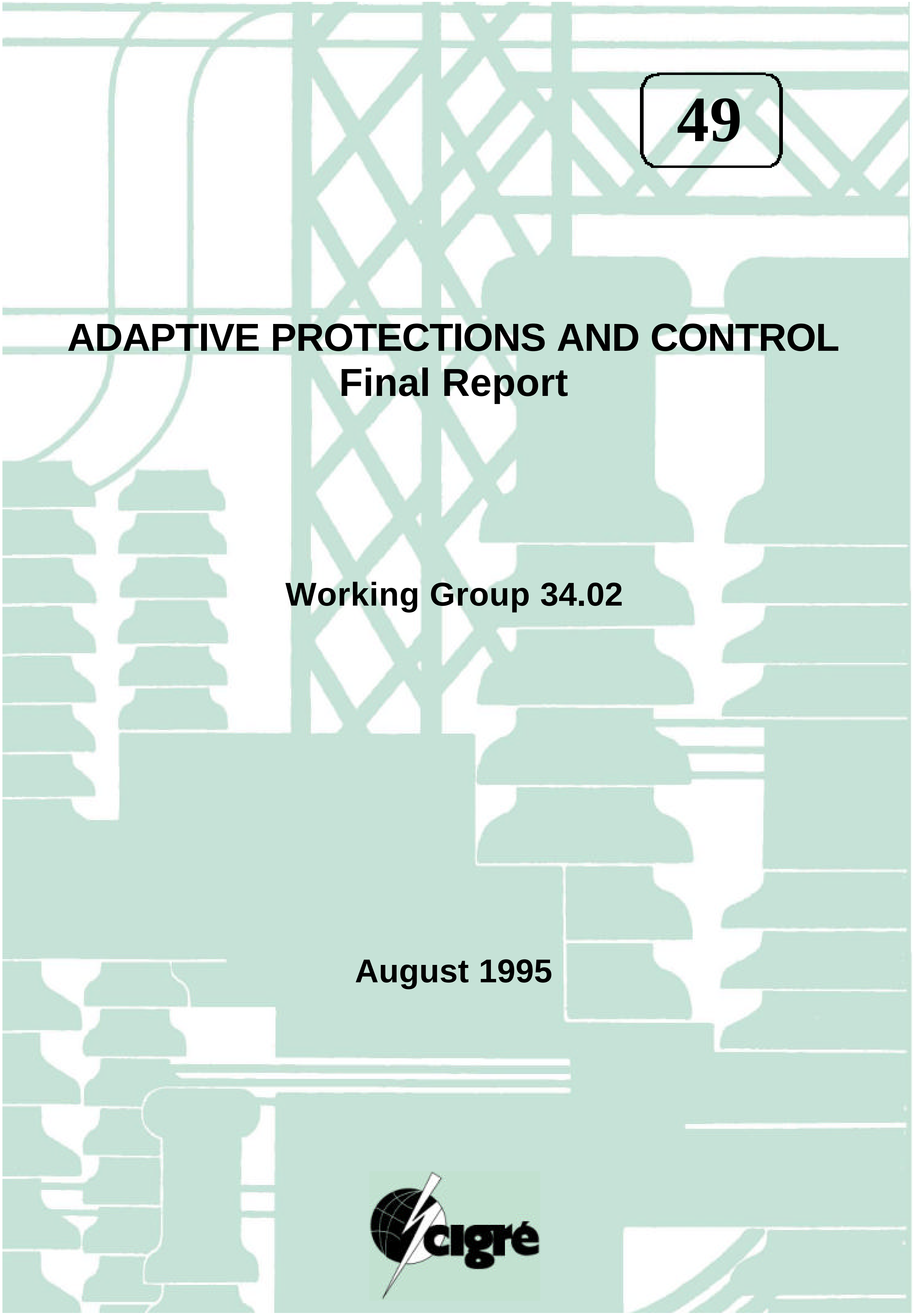

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ADAPTIVE PROTECTIONS AND CONTROL
Final Report

Working Group 34.02

August 1995

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FOREWORD

This report is prepared by Working Group 34.02 of Study Committee 34, 'Protection and Local Control' of the Conference Internationale de Grande Reseaux Électrique (CIGRÉ). The working Group membership was as follows:

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EXECUTIVE SUMMARY

The concept of *adaptive protection and local control* recognizes the possibility that quite often the settings of various protection and control devices as determined by extensive simulations of power system contingencies, are dependent upon certain assumptions about the nature of prevailing power system loading, generation, and status of various transmission facilities. Consequently, the settings of these devices, although appropriate for conditions which were assumed to exist when the simulations were made, may no longer be appropriate, or even correct. Also, there is the possibility that in order to meet the requirements imposed by several foreseeable contingencies, the actual settings used are not optimum for the prevailing system conditions. The concept of adaptive protection and control recognizes these possible shortcomings of the settings, and explores methods by which the settings in question could be altered to match the prevailing conditions of the power system. Clearly, adaptive protection and control pre-supposes computer based relays and control systems. Computer based systems could accept inputs from external sources over communication lines, and act on these inputs to alter and improve their settings. Truly adaptive capabilities would be difficult to realize in electromechanical or analog solid-state systems.

This report includes the results of a survey of practicing protection and control engineers in all the member countries, which sought the experts' views on the need, feasibility, desirability, and possibilities for practical implementation of adaptive relaying concepts. After summarizing the results of the survey, the report examines several other adaptive relaying possibilities in detail, including a study of the communication systems needed to implement the adaptive features. The working group also recognized the need for secure fall-back positions, in case the adaptive features or the communication systems fail. A discussion of these and other issues relating to adaptive protection and control system implementation will be found in the report.

It is not surprising that a number of adaptive features have already been investigated and implemented in existing systems. Some of these implementations are quite simple, and indeed may not be thought of as being adaptive in the sense of the definition of the term accepted by the working group. For example, a time over-current relay may be considered to be adaptive - as it adapts its operating time to the level of the fault current. However, the definition accepted by the working group implies that a truly adaptive protection system must use information not normally available to the system to accomplish its task, and hence the time over-current relaying function can not be considered to be adaptive. Nevertheless, this report includes examples of adaptive systems which may not be in strict compliance with the accepted definition. This was a deliberate decision of the working group since this is the first study of this subject in CIGRÉ, and the working group wished to make it all-inclusive at this early state of development.

There are indications that the subject of adaptive protection and control has captured the imagination of protection engineers throughout the world. The number of technical papers dealing with this subject has increased significantly over the last several years. This report includes results of research projects and experimental field installations of adaptive protection and control systems. It is expected that as experience with these experimental systems is gained, the principles of adaptive protection and control will find even greater acceptance, leading to improved economy and security in operation of power systems.

1. INTRODUCTION

The concept of adaptive protection evolved during the 1980's. By then, digital computer based relaying was well accepted. Most relaying functions have been shown to be amenable to digital computer implementation, and the satisfactory field experience with these devices has allayed the fears of protection engineers about the survivability of computer relays in the harsh environment of electric utility substations. From the very beginning when earliest experiments with computer relays were being carried out, the possibility of being able to change the relay characteristics under external control has intrigued relay engineers. The field of adaptive relaying is the culmination of efforts in that direction.

It has been noted [1] that major power system blackouts often have inappropriate relay system performance as one of the contributing factors. Leaving aside hidden relay system failures, a significant factor in major power system outages is the inappropriate settings of relays for the prevailing power system state. Often, the settings have been made many years ago, and were appropriate at that time. However, as the power system evolves, the system conditions may have changed, and the existing relay settings may no longer be appropriate. Also, sometimes a relay setting is a compromise designed to cover a large variety of operating conditions, thereby making the setting far from optimum for any single operating state. Arguments of this nature call for relays whose settings can be controlled in response to external conditions. In this connection, it should be noted that many relays in use at present have adaptive features. For example, an over current relay adapts its operating time to the prevailing fault current magnitude.

Formally, adaptive relaying has been defined as follows: "Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions." This definition was first provided in a slightly different form in reference [2], and has been accepted by an IEEE working group on adaptive protection [3]. A number of other publications have also accepted this definition.

If this definition is broken into smaller clauses, three significant requirements of an adaptive protection system can be identified from the specific wording in the definition:

(1) **"permits and seeks to make adjustments":** This means that the protection system itself either permits predetermined adjustments to be made based upon information received from the outside world, or tries to find adjustments within itself.

(2) **"automatically":** Closed loop arrangements have to be used.

(3) **"attuned to prevailing power system conditions":** In order to bring in the prevailing power system conditions, information could be extracted either from the normal measurement quantities or from auxiliary signals which are supplied to the protection system from outside.

All these are ***necessary requirements*** to obtain an adaptive protection system. However, it can be anticipated that early implementation of adaptive protection systems may disregard some of these characteristics.

1.1 Differences between traditional and adaptive systems

A traditional, non-adaptive, protection system will have a generic model as shown in Figure 1.1.

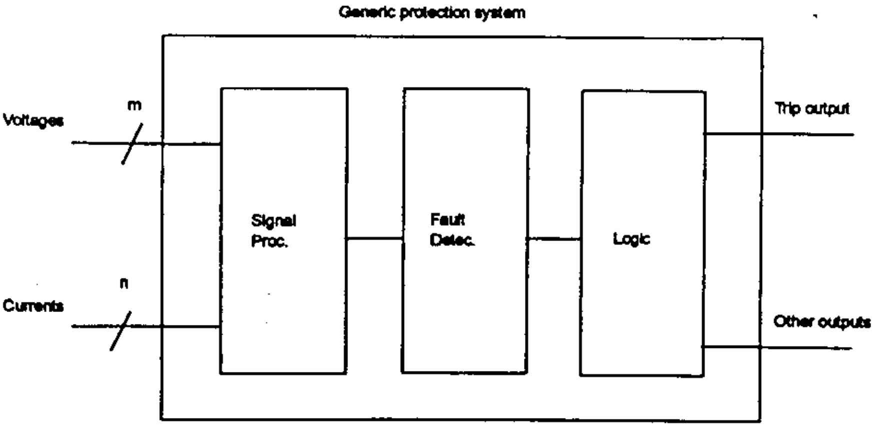

Figure 1.1: Generic protection system.

In order to obtain an adaptive system which meets the three main requirements described above the model has to be modified according to Figure 1.2, which is a generic model for an adaptive protection system.

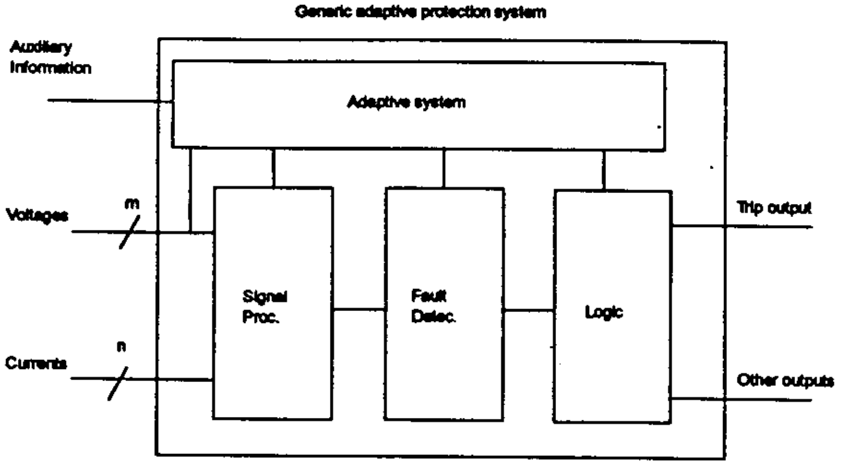

Figure 1.2: Generic adaptive protection system.

In a given adaptive protection implementation, we may see different approaches depending upon which part of the protection system is affected, and which signals are used as inputs. However, basically the adaptive system has to recognize a certain set of input data and then produce some output which can be used to effect a change in the protection system.

The separation between the scheme used by an adaptive system and the traditional logic based upon signal processing, fault detection, etc. is very important in order to obtain the desired fall-back position. If the adaptive features do not work properly, the normal protection function is akin to feedback control and continues to operate as designed. The information about the prevailing state of the system is fed back to the adaptive protection system, and is used to determine a change in the protection system which would help achieve a desired goal. In contrast to a feedback control system, the feedback provided for adaptive relays may not alter the relay system performance in real-time - at least at the present time. Rather, the parameters of the protection system characteristics may be altered and the effect of these alternative settings would be felt only if a fault within the zone of the protection system occurred. No doubt, as experience with adaptive protection is gained, we may see other evolutionary changes in these concepts. In any case, it seems clear that with the advent of adaptive relaying, the gap between the fields of protection and control has narrowed considerably.

Clearly, the ability of computer relays to communicate with external systems is a key element of adaptive protection systems. The role of communication systems will be emphasized repeatedly in this report. It will become clear that communicating over wide ranges of channel speeds, and over varying distances provide adaptability of different kinds and degrees. Even rudimentary communication links can provide significant adaptive capability, and systems can be designed so that the loss of communication links will not degrade the normally available non-adaptive protection functions.

In the following pages the ideas of adaptive protection philosophy will be described in greater detail, and several examples of emerging adaptive technology will be presented. The report also includes the results of an industry survey conducted by the working group in order to assess the feelings in the relaying community about the subject of adaptive relaying. Also included in the report are a number of potential opportunities for adaptive relaying. Several preliminary studies of adaptive relaying have already been reported in the literature. It is to be expected that as experience with computer relays grows, more and more adaptive relaying systems will be the subject of active investigations.

2. OPPORTUNITIES FOR ADAPTIVE PROTECTION - A SURVEY

2.1 Introduction

In order to determine industry acceptance of adaptive relaying and control, a survey was conducted by the Working Group similar to, but not identical with, one distributed by the IEEE Power System Relaying Committee [3]. The experience of the IEEE survey led to modifications to the CIGRÉ questionnaire to clarify the responses. Also, since the IEEE survey targeted only the U.S. relay engineers, the CIGRÉ questionnaire included areas of protection and control that could differ from U.S. practices such as acceleration schemes, single-phase tripping and reclosing, out-of-step and generator protection. A CIGRÉ questionnaire was sent to a sampling of North American relay engineers to establish a correlation between the two surveys. It is our intention to review in this chapter the results of the IEEE survey, to analyze the results of CIGRÉ W.G. 34.02's survey and to combine both efforts in a comprehensive world-wide view of the feasibility and acceptance of adaptive relaying and control. A copy of the survey developed by the working group will be found in Appendix I.

The respondents to the IEEE survey included engineers ranging from relay engineers to chief engineers with an overall average of 17.74 years of protective relaying experience. The respondents were primarily from operating utilities (82 vs. 8 others), with transmission line voltages from less than 115 kV (2544 miles) to above 345 kV (575 miles). The average peak load was 4115 MW. The CIGRÉ survey encompassed 59 utilities, 13 manufacturers and 8 others. The respondents represent a range of responsibilities from engineer to chief engineer with an average of 14.28 years of experience. The utilities had transmission lines and cables ranging form 92 kV to 422 kV and an average peak load of 14827 MW. For the comparison with the IEEE survey, the 10 North American responses in the present survey were all from utilities whose engineers averaged 18.2 years of experience and had transmission line voltages from 46 to 765 kV.

Part I of both questionnaires provided the respondents with the opportunity to express their satisfaction with existing relaying schemes. The IEEE data quantified satisfaction with various relaying schemes with separate bar charts for solid-state and electromechanical relays as shown in reference [3]. The CIGRÉ questionnaire requested yes-no responses regarding functional satisfaction with the equipment used for the various relaying schemes. Digital relays were included as a separate item as were generation protection schemes.

The second part of both questionnaires is a list of possible adaptive functions whose value the respondents were asked to rate on a scale of 1 to 7 with 7 being very valuable and 1 being not needed. In addition, the respondents were asked whether the functions were available in existing relays.

2.1.1 Overall Survey Results

As noted above, the first part of the questionnaire provided the respondents with the opportunity to express their satisfaction with existing relaying schemes. The functions were separated into: transmission line, transformer, bus and breaker, and generator protective relaying functions. The transmission line protective relaying functions are listed in Table 2.1. The following bar graphs indicate the satisfaction of the respondents with the various functions as an index of "Improvement Needs" computed as follows:

Index of Improvement needs

$$= \frac{[(\text{Number of YES answers} - \text{Number of NO answers})(\text{Number of Answers} - \text{Number with NO experience})]}{(\text{Number of Answers})^2}$$

The above formula can be viewed as being made up of two factors. The first factor,

(Number of YES answers - Number of NO answers)/(Number of Answers)

indicates the relative balance between the respondents who favor an improvement through adaptive relaying, and those who are satisfied with the existing practice. All answers favoring changes would lead to a value of 1.0 for this factor, whereas if all respondents were satisfied with existing relaying, this factor would be -1.0. The second factor,

(Number of Answers - Number of with NO experience)/(Number of Answers)

indicates a weight which may be attached to the first factor, depending upon whether the responders have experience with a given function. Thus, if all respondents had no experience with the protection in question, the above index would represent a complete rejection of the response. When the respondents gave a certain level of support to an adaptive concept, the second factor would weight this response according to whether the respondents had no experience upon which to base this judgment. Clearly, there are other ways in which these ideas could be quantified. Ours is one such index. This index is computed for each of the protection functions, and is shown as a bar graph expressed as a fraction of 1.0, or as a percentage.

As mentioned previously, Table 2.1 provides a listing of functions dealing with transmission line protection. The corresponding bar graphs of "Index for Improvement Needs" use the numbers from this table to identify the individual functions. This is done in order to avoid crowding the vertical axis of the bar graphs. In other functions, where the number of functions is small, the actual functions are put on the bar graphs.

1	Multiphase faults	4h	Non-Segregated differential
2	Earth distance	4i	Segregated differential
3	Earth fault overcurrent	4j	Non segregated pilot wire differential
4a	Directional comparison	4k	Segregated pilot wire differential
4b	Unblocking	4l	Other Pilot relay
4c	Permissive overreach	5a	Single phase tripping and reclosing
4e	Direct underreach	5b	Time delays
4f	Acceleration	6	Multiphase tripping and reclosing
4g1	Segregated phase comparison	7	Out-of-step detection
4g2	Non-segregated phase comparison	8	Other

Table 2.1: Transmission line protective relaying functions.

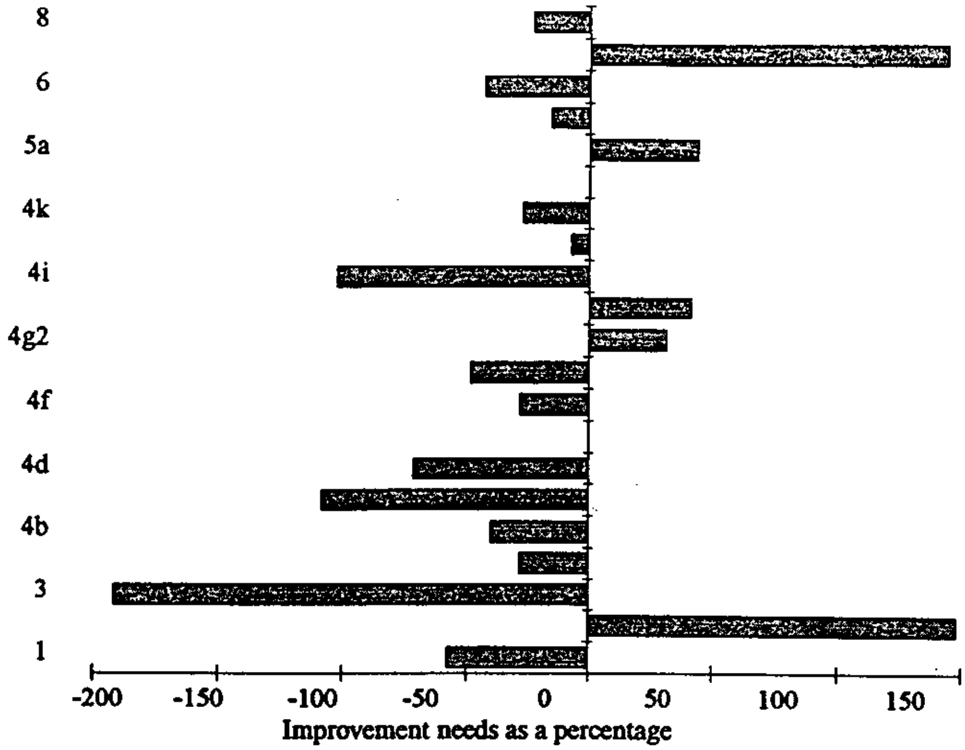

Figure 2.1: **Improvement Needs for Transmission Line Relaying Functions for the total response to Part A of the Questionnaire.**

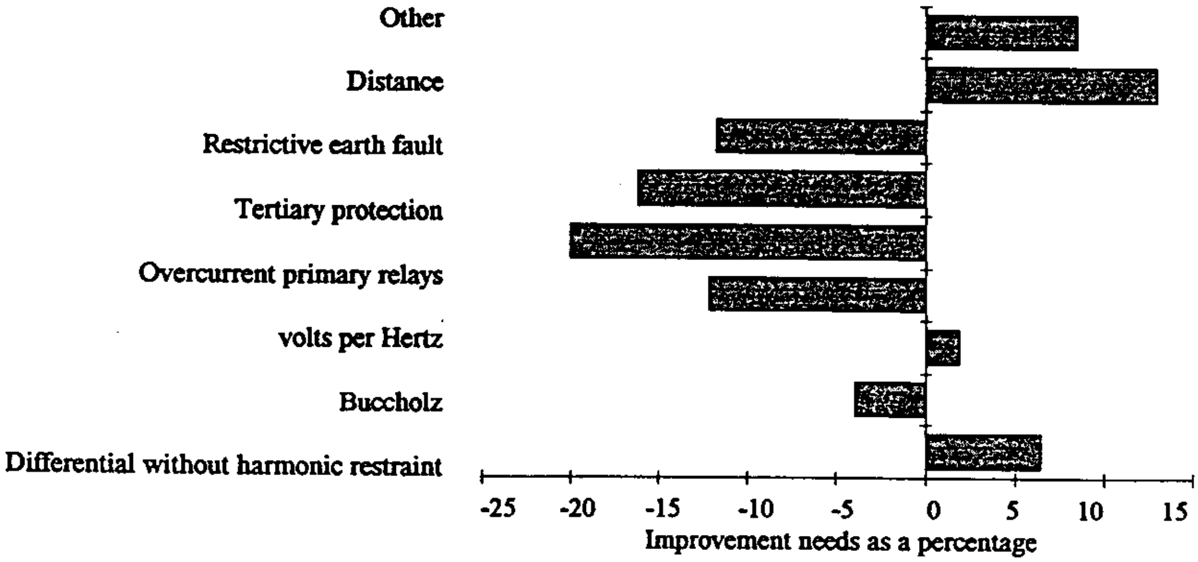

Figure 2.2: **Improvement Needs for Transformer Protective Relaying Functions for the total response to Part A of the Questionnaire.**

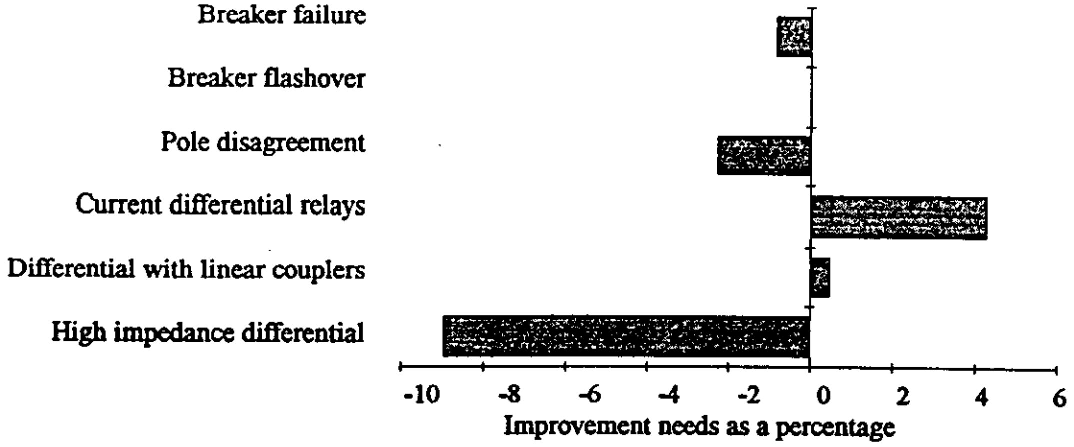

Figure 2.3: Improvement Needs for Bus and Breaker Protective Relaying Functions for the total response to Part A of the Questionnaire.

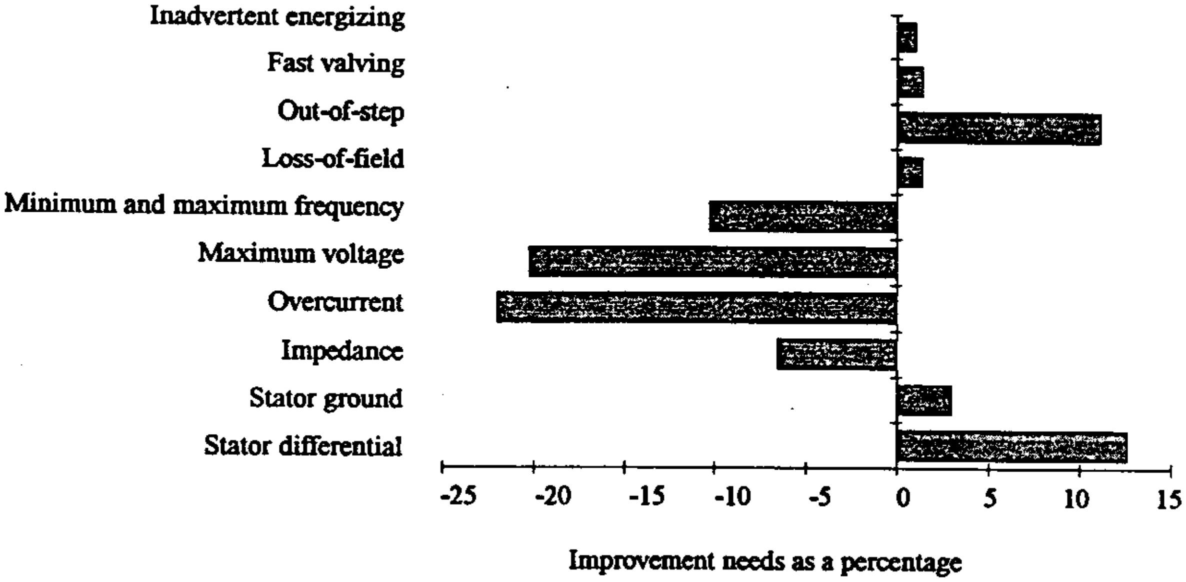

Figure 2.4: Improvement Needs for Generator Protective Relaying Functions for the total response to Part A of the Questionnaire.

2.1.2 Section B Adaptive Functions

The second part of the questionnaire was a list of 17 possible adaptive functions whose value the respondents were asked to rate. Specifically the respondents were asked to answer the following for each of the 17 adaptive features:

> *In your opinion, on a scale of 1 to 7 (with 7 being very valuable and 1 being not needed), how valuable is it or would it be to have relays adapt to the*

following situations. Note that the question has two parts. In part (b) please indicate if in your view the adaptive feature is available or not available to you in your relays or if you are using the feature. If so, would you please indicate the type of relay which provides the feature.

The 17 adaptive functions are listed in Table 2.2.

Each of the questions along with the mean and standard deviation of the responses are given in Figure 2.5. The lower (solid) bar next to each relaying schemes indicates the mean of the respondent's rating of the scheme and the second bar is the standard deviation (σ) of the rating. For example, the mean rating of adaptive feature 5, "Load Flow Compensation" was 5.85 (out of 7.0) and the standard deviation was approximately 1.5 (the responses are concentrated near 5.8).

Overall, qustions 5 (Load flow compensation), 7 (Multi-terminal distance relay coverage) and 13 (Proactive load shedding) have strong support for adaptive features, whereas questions 8 (Variable breaker failure timing), 11 (Sympathy trip response), and 16 (Bus protection restraint for arrester applications) have relatively weak support. Even though the statistics are less meaningful when only a few respondents answer that question, there is sufficient variation between the responses in different parts of the world to present the results by area. This is done for selected areas in the following sections.

1(a)	Operating time as a function of the distance to fault
2(a)	Mutual coupling compensation in ground impedance protection
3(a)	High source impedance ratio (SIR) changing
4(a)	Remote end open breaker detection for high speed sequential tripping
5(a)	Load flow compensation
6(a)	Fault type (multi-phase vas. single phase) changing speed of operation
7(a)	Multi-terminal distance relay coverage
8(a)	Variable breaker failure timing
9(a)	Permissive reclosing
10(a)	Adaptive reclosing
11(a)	Sympathy trip response
12(a)	Adaptive synchronism check angle for reclosing
13(a)	Proactive load shedding
14(a)	Adaptive transformer differential protection
15(a)	Voltage change supervision of differential unit
16(a)	Bus protection restraint for arrester applications
17(a)	Adaptive protection and control

Table 2.2: Adaptive relaying functions from Part B of the Questionnaire.

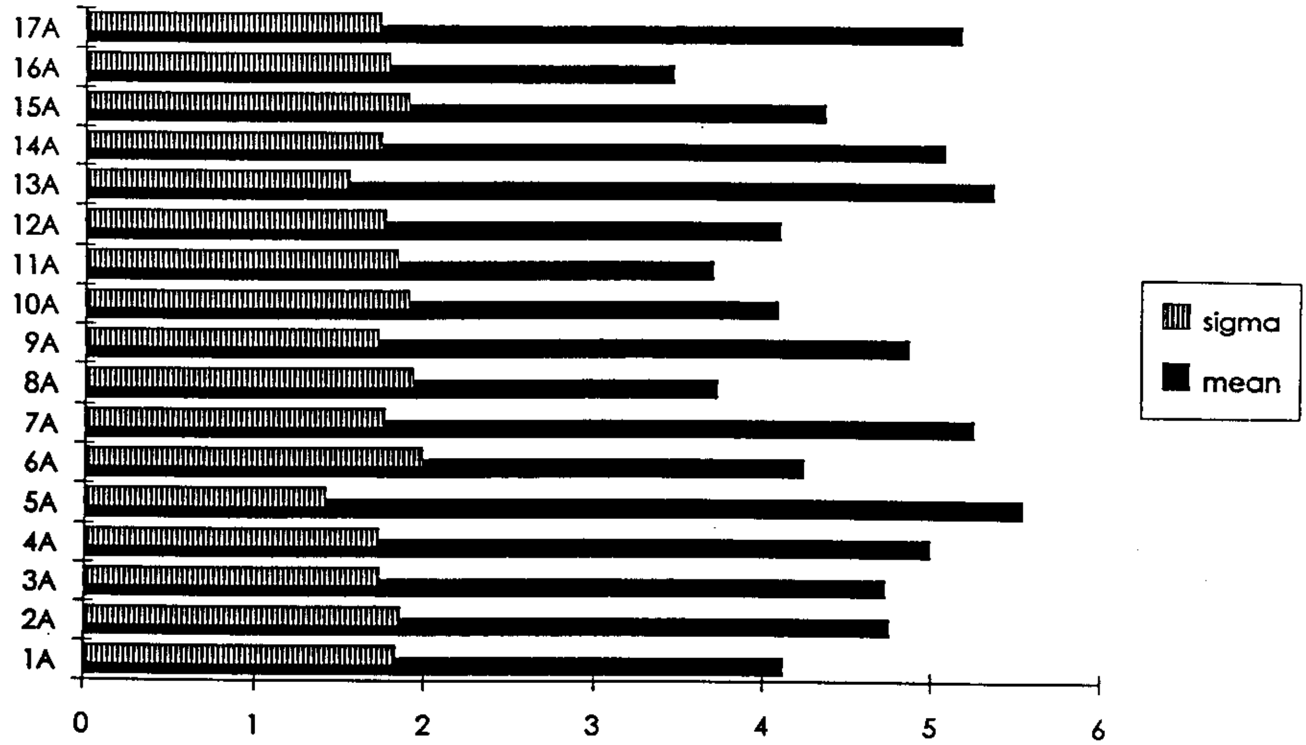

Figure 2.5: Summary of Survey Responses to Section (B). The mean and standard deviation of the rating index for each scheme.

2.2 Statistical Analysis and Comments on the answers from Spain and Portugal

2.2.1 Statistical Analysis

Average and standard deviation of answers to questions 1 to 17 have been calculated, and are presented in Figure 2.6.

2.2.2 Comments on the answers

2.2.2.1 There are no significant differences between the answers from utilities and manufacturers.

2.2.2.2 There are no significant differences depending of the voltage level, peak load or other factors.

2.2.2.3 Most valued features of adaptive protection chosen by the respondents (with average greater than 6 are):

- Operating time as a function of the distance to fault
- Mutual coupling compensation in ground impedance protection
- High Source Impedance Ratio (SIR) changing
- Load flow compensation
- Multi-terminal distance relay coverage

- Permissive reclosing
- Adaptive transformer differential protection

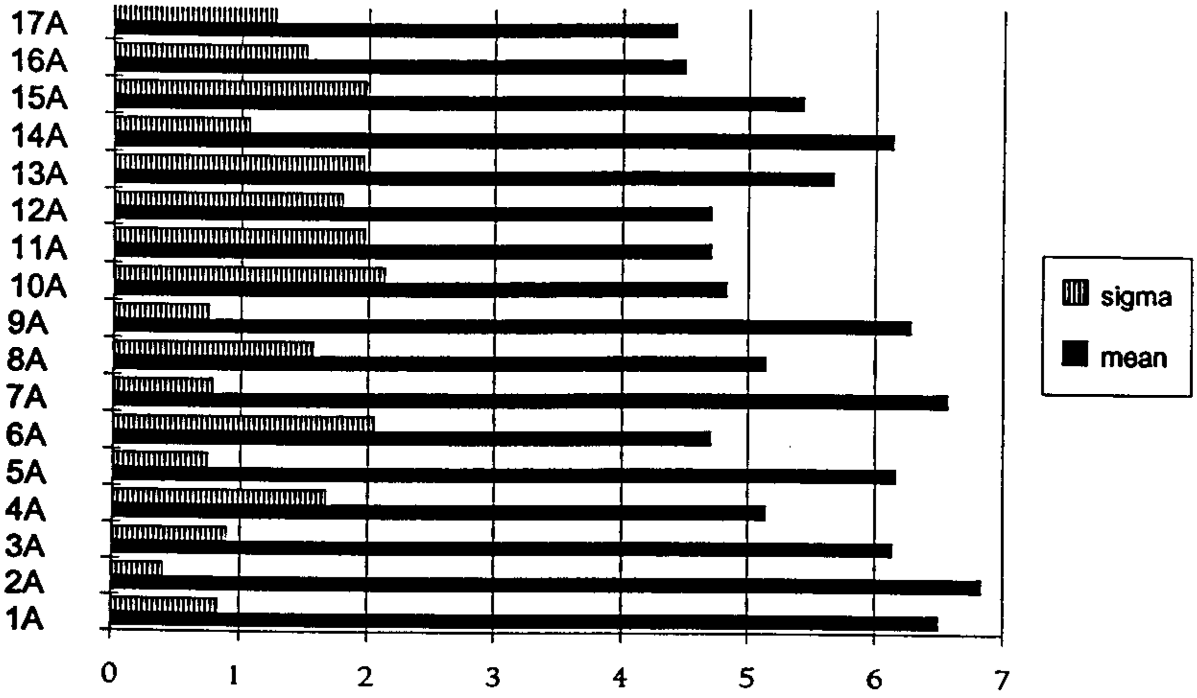

Figure 2.6: Summary of Survey Responses from Spain and Portugal to Section (B). The mean and standard deviation of the rating index for each scheme.

2.2.2.4 Least valued features of adaptive protection according to the respondents (with average less than 5 are):

- Fault type changing speed of operation
- Adaptive reclosing
- Sympathy trip response
- Adaptive synchronism check angle for reclosing
- Bus protection restraint for arrester applications
- Adaptive protection and control

2.2.2.5 Features with highest degree of agreement among the respondents (with standard deviation less than 1 are):

- Operating time as a function of the distance to fault
- Mutual coupling compensation in ground impedance protection
- High Source Impedance Ratio (SIR) changing
- Load flow compensation
- Multi-terminal distance relay coverage

- Permissive reclosing
- Adaptive transformer differential protection

These features are the same as those considered to be the most valued features.

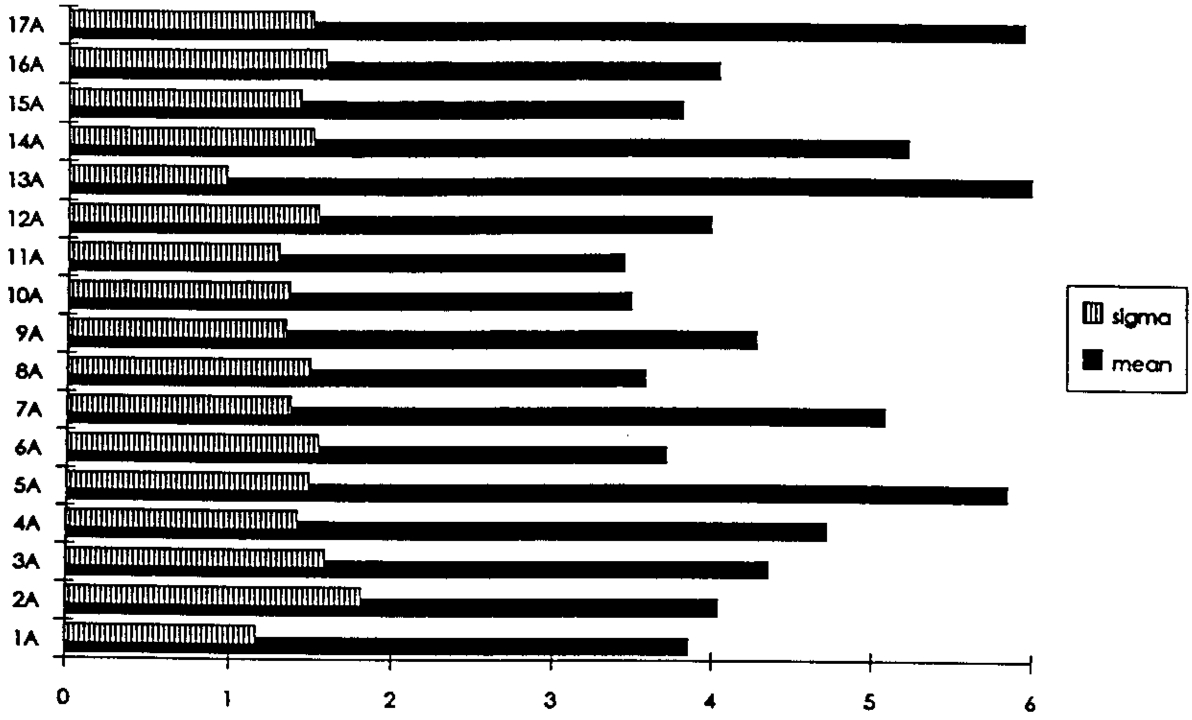

Figure 2.7: **Summary of Survey Responses from West Pacific.**

2.3 Statistical Analysis and Comments on the answers from West Pacific.

2.3.1 West Pacific

There were 18 Japanese responses, (ten from utilities, seven from manufacturers, and one from a research institute), and four responses from overseas utilities (one each from Australia, Korea, Republic of China, and Thailand). The number of overseas responses is not large enough to deal with statistically, however, there are obvious trends differing from Japanese responses on some items.

2.3.2 Part I - Responder's Particulars

The greatest need for improvement was indicated from overseas utilities on distance relays for multi-phase faults, ground distance, overcurrent ground relays, directional comparison blocking, non-segregated pilot wire, out-of-step, sudden pressure relaying and inadvertent energization. The need indicated from Japanese utilities was, however, only on single phase tripping and reclosing (time delay), out-of-step and sudden pressure. Although Japanese manufacturers recognized the need for improvements on distance relays, Japanese utilities do not perceive the need. The manufacturers expected the best capability of distance measurements with digital technology.

Other relays receiving fewer votes for need for improvement from Japanese utilities included relays which will not be installed now or in the near future, because they have less favorable characteristics, such as over current ground relays (inverse or definite time), phase comparison, pilot wire, and transformer differential without harmonic restraint. At the time when the survey was conducted, digital relays were widely used in Japan, but not to such an extent overseas.

2.3.3 Part II - Adaptive Protection possibilities

The mean and standard deviations of responder's ratings on questions 1 through 17 are shown in Figure 2.7. As shown in the figure, '5: Load flow compensation', '13: Proactive load shedding', and '17: Adaptive protection and control' were rated as being the most valuable, and '4: Remote-end open-breaker detection', '7: Multi-terminal distance relay coverage', and '14: Adaptive transformer differential protection' were rated as valuable. Although the mean is less for these items: '2: Mutual coupling compensation in ground impedance protection', and '3: High source impedance ratio (SIR) changing' were supported as the most valuable by the overseas utilities.

Seven adaptive functions shown in Items 18 through 24 of Appendix III were suggested from Japan. Items 18 through 20 fall within Item 17, however, the three functions have noticeable differences among themselves. Many responses from Japan indicated that the utilities are using several functions as shown in Table 2.3. Relay types applied for those functions are 'Toshiba-D2 series', 'Mitsubishi-M32 series', 'Fuji-DUCU series', 'Meidensha-MR series', and 'Hitachi-JDR series'.

	Functions	Number of votes for 'Using'/Total
5:	Load flow compensation	13/18
6:	Fault type changing speed of operation	2/18
13:	Proactive load shedding	8/18
16:	Bus protection restraint for arrester applications	2/18
17:	Adaptive protection and control	11/18
18:	Real-time prediction type stabilizing protection	2/2(1)
19:	Lost power compensation type stabilizing protection	2/2(1)
20:	On-line stability calculation type stabilizing protection	0/1(2)
21:	Change of mutual coupling compensation depending on comparison of zero sequence currents	1/1(1)
22:	Adapting converting of protection scheme	2/3

Note (1): The functions were widely applied in several utilities in Japan, however, those were suggested by only a few responders.

Note (2): The function was reported as 'Not available', however, the function is expected to be commissioned in June 1995.

Table 2.3: Functions reported as being used in Japan.

2.4 Statistical Analysis and Comments on the answers from Switzerland

The questionnaire has been sent to responsible engineers in operating utilities only .There are very few answers per country, but all answers, shown in Table 2.4 represent the view of users. Apparently there is a low average rating from Austria and especially from Germany. Both countries have a long tradition and a good performance of existing protection schemes. In such circumstances a need for change is not very strong. But even in Germany, the rating for the "Load Flow Compensation" (5a) was high.

Question	Austria (2)	Germany (4)	CH (1)	Czech Rep. (2)	Abu Dhabi (1)
1A	3	2.75	2	2	1
2A	4.5	3.5	3	2	7
3A	2.5	3.25	4	3	1
4A	4	3	6	4	7
5A	3.5	5	5	5.5	7
6A	3.5	4	6	3.5	1
7A	3.5	2.25	5	5	7
8A	3	2.25	1	4.5	5
9A	3	2.75	7	5.5	7
10A	2.5	2.75	5	6	7
11A	4	1.25	3	4.5	7
12A	3	2.75	2	2	7
13A	4	2.5	4	4	3
14A	4	2.75	6	6	7
15A	5.5	3.25	7	5	1
16A	2	1.75	2	4	1
17A	1	1.75	7	5	
18a					
Average (1-17)	3.32	2.79	4.41	4.21	4.75
Overall Average	3.53				

(X) = Number of Questionnaires

Table 2.4: Survey Responses as collected in Switzerland.

2.5 Statistical Analysis and Comments on the answers from UK and South Africa

Fifty one questionnaires were issued to selected established protection engineers from which there were seventeen respondents (a 30% response rate). Of the seventeen responses, eleven were from utilities, two from manufacturers, two from academic organizations and two from consultants, thus giving a reasonable balance of views. All respondents had many years of experience in their particular field ranging from 6 to 40 years with an average of 22 years and held influential positions in their organizations. There were no significant differences between answers

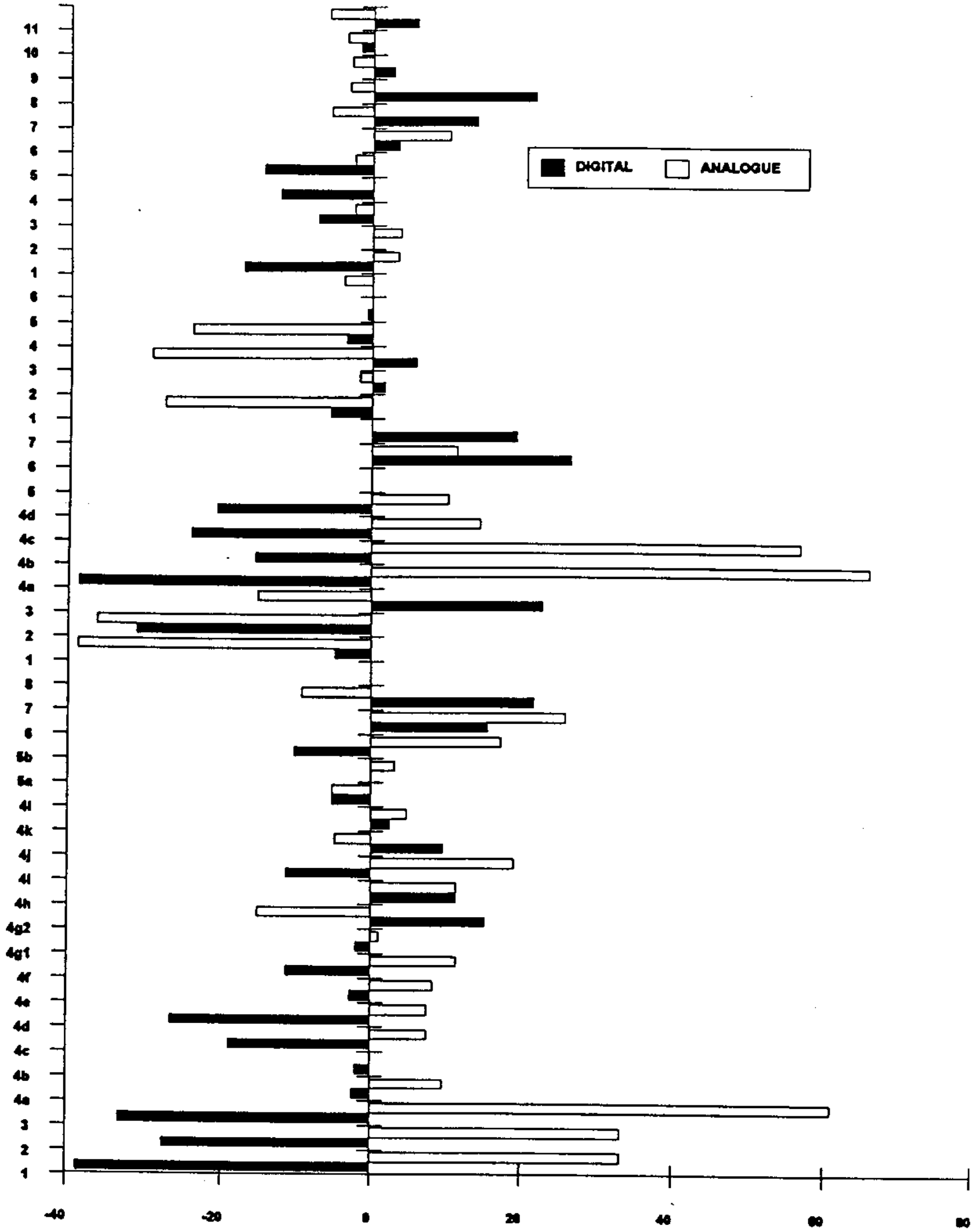

Figure 2.8: Summary of UK and South Africa responses to part 1 of questionnaire.

from different groups, i.e. manufacturers were not polarized with one view and utilities with another, nor South Africa with one view and UK with another.

In order to give a graphical display to part 1 of the questionnaire the responses for analog and digital protections were used to calculate the Index for Improvement Needs as defined earlier in section 2.1.1.

The display of these results is shown in Figure 2.8 and indicates that there is a general satisfaction with existing relay schemes but that with more modern digital protections there was a perception that improved functionality/adaptability should be achievable and expected. Figure 2.9 shows the respondents ratings to part 2 of the questionnaire. (i.e. the desirability of 17 possible adaptive protection functions.)

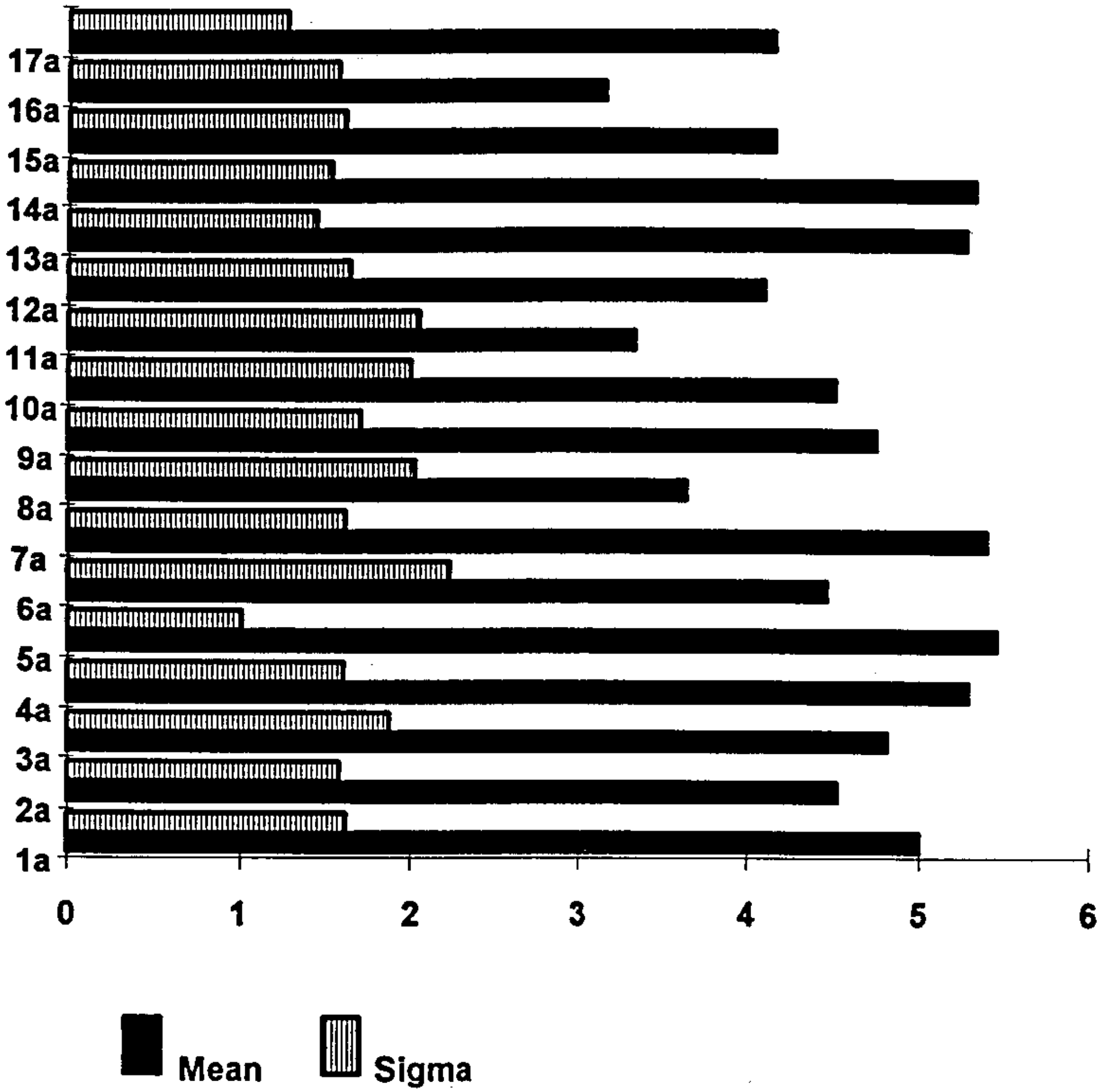

Figure 2.9: UK and South Africa survey responses to part 2 of questionnaire.

The responses indicated that there was little adaptive protection capability available in present protection systems, but that there was a definite perception that it would be beneficial. All 17 possible adaptive protection functions achieved a high mean value and a relatively small standard deviation on a scale of 1 to 7 (7 being most desirable).

- 5 functions exceeded a rating of 5
- 14 functions exceeded a rating of 4
- 17 functions exceeded a rating of 3

2.6 Regional Survey Results from Belgium and The Netherlands

2.6.1 General considerations

This regional analysis concerns 7 answers from Belgium and one from The Netherlands. The single answer from the Netherlands is given by the CIGRÉ SC34 member and should normally cover all utilities. That means a peak load of 10GW and 2490km of 380-220kV lines, 5608km of 150-110kV lines and 747km of 150 110kV cables.

Four of the Belgian responses are given by people working for the main utility. The peak load is 11GVA and there are 1660km of 380-220kV lines, 5165km of 150-70kV lines and 259km of 150-70kV cables. The 3 other Belgian answers come from an industry with a considerable distribution network, a university specialized in protection systems and a laboratory working for the Electricity industry in Belgium. The average number of years of experience in Belgium is 18.7 years (20 years for the overall survey).

2.6.2 The first part of the survey

In the first part the opinion is asked about improvements in different protection functions. The comparison with the overall survey gives the following results:

- there is the same demand for improvement in the ground distance function (2), in distance relays on transformers (7), and for single phase tripping and reclosing (5a).
- there is a clear need for improving the non segregated current differential function (4h), the transformer differential function and the buchholz relay.
- no other improvements are sought unanimously.

Considering these results it seems that most of the users are fairly happy with the actual protection systems in use.

2.6.3 The second part of the survey

Here, the opinion is asked about a list of adaptive features. The results are given in Figure 2.10. As can be seen, the most popular (mean greater than 5) features are adaptation to high Source-Impedance-Ratio, Remote-End Open-Breaker detection, permissive reclosing, Proactive load shedding and adaptive protection and control. Compared to the overall survey result (Figure 2.1) there is some agreement except for some specific functions:

- operating time as a function of distance to fault, voltage change supervision and Bus protection restraint for Arrester are not considered to be very desirable
- load flow compensation has some interest but less than in other countries

The differences in desires can be explained by the particularities in the network.

The mild interest in load-flow compensation is surprising. It has a positive influence on phase-selection in distance protections, which is one of the major concerns in meshed networks with single-phase tripping as those used in Belgium and the Netherlands. Moreover, it already exists in different distance protections used in those countries.

As in the general survey there is a duality between the desire for using the adaptive functions listed in part 2 of the survey and the satisfaction with the protection functions as they are identified in part 1 of the survey.

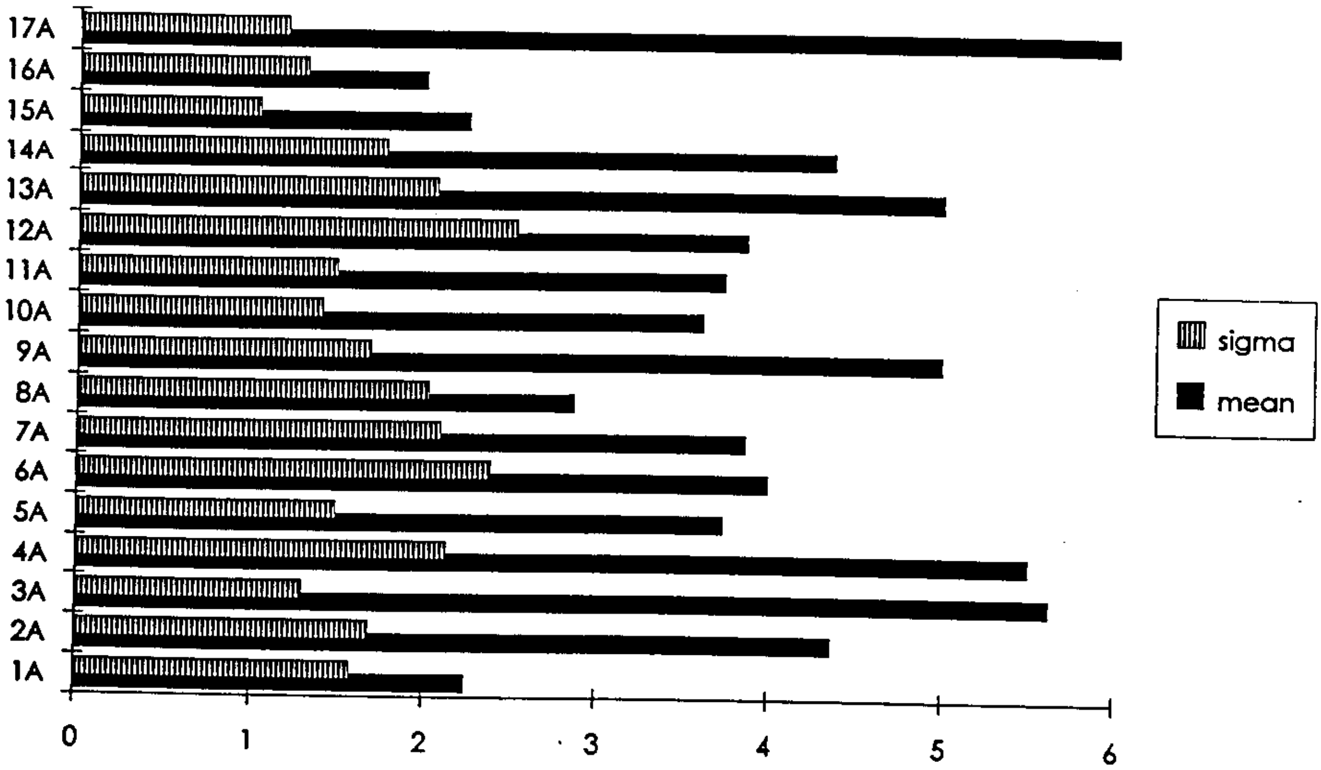

Figure 2.10: Summary of Survey Responses to Section (B). Regional results from Belgium and the Netherlands.

2.7 Statistical Analysis and Comments on the answers from Italy, Albania, and Greece

This section contains a summary of the responses received from the questionnaire sent last year to engineers in Italy, Albania and Greece. Twenty questionnaires were sent (18 in Italy, 1 in Albania, 1 in Greece); 10 responses were received: 8 from Italy, 1 from Albania and 1 from Greece. A summary of the responses is included in this section.

2.7.1 Preliminary data

2.7.1.1 Respondent

Responders are almost completely from Utilities. Only one respondent (from Albania) works in an Academic Institution. All the categories of responsibility were represented, although not in equal numbers. No Supervising Engineer or Professor responded. Only the construction field is not represented. The responders' years of experience with protection range form 5 to 28 years. The mean value for experience is 16.7 years.

2.7.1.2 Utility data

Peak loads range from 330 to 36300 MW. The mean value is 25460 MW.

2.7.2 Experience with protection systems

2.7.2.1 Transmission lines

Need for improvements is present in almost all cases, with the exception of 4f (teleprotection, acceleration scheme), while in cases 4j (teleprotection, current differential, non segregated), 4k (teleprotection, current differential, segregated) and 5b (single phase tripping and reclosing, time delay),the positive and negative responses are equally divided. In case 4e (teleprotection, direct underreaching) all the responders showed no experience. In Figure 2.11, YES and NO responses are represented in normalized values, i.e. taking into account only the responses with a declared experience. Digital relays are used in 7 out of 19 cases (40 %) in 27.3 % of responses.

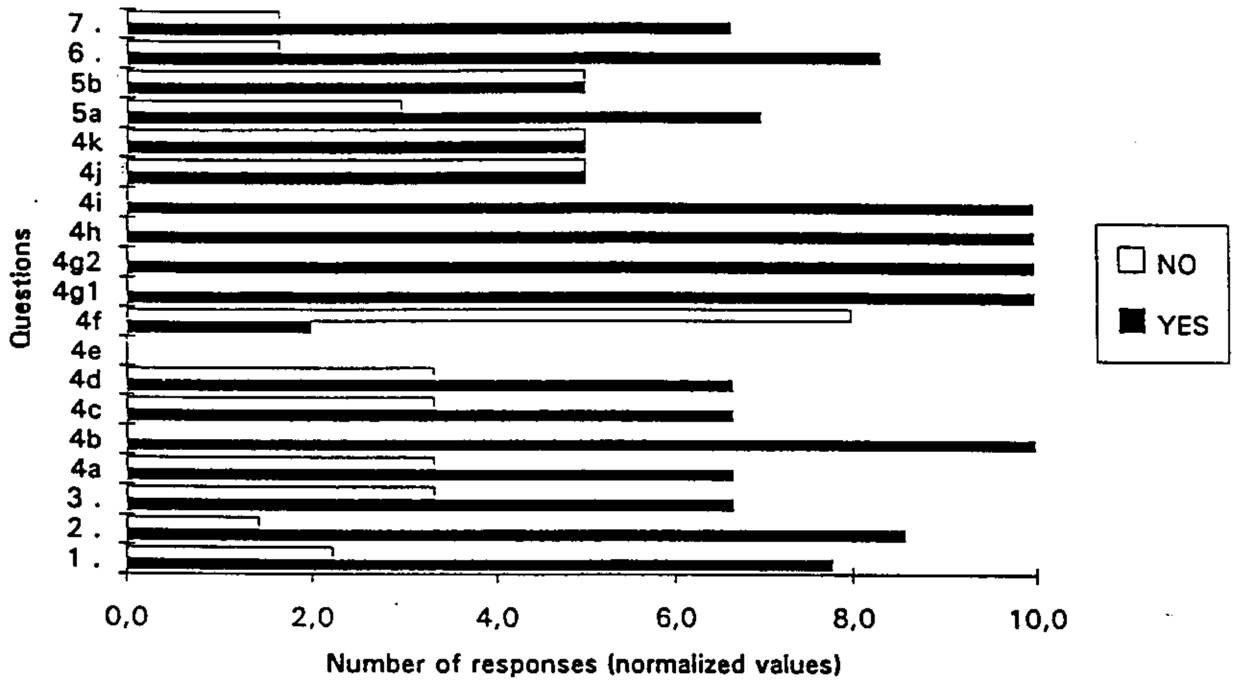

Figure 2.11: Improvement Needs for Transmission Line Relaying Functions.

2.7.2.2 Transformers

Need for improvements is indicated in almost all the cases, with the exception of case 2 (Buchholz). An equal proportion of YES and NO responses is present in cases 4c (Overcurrent relays, tertiary protection) and 4d (Overcurrent relays, neutral protection), see also Figure 2.12. Digital relays are used in 6 out of 8 cases (75 %) in 21.1 % of responses.

2.7.2.3 Bus and breakers

Need for improvements is indicated in almost all cases, with exception of case 1 (High impedance differential relays). An equal proportion of YES and NO responses is present in case 6 (Breaker failure protection), see also figure 2.13. Digital relays are used only in 1 out of 6 cases (16.7 %) in 4 % of responses.

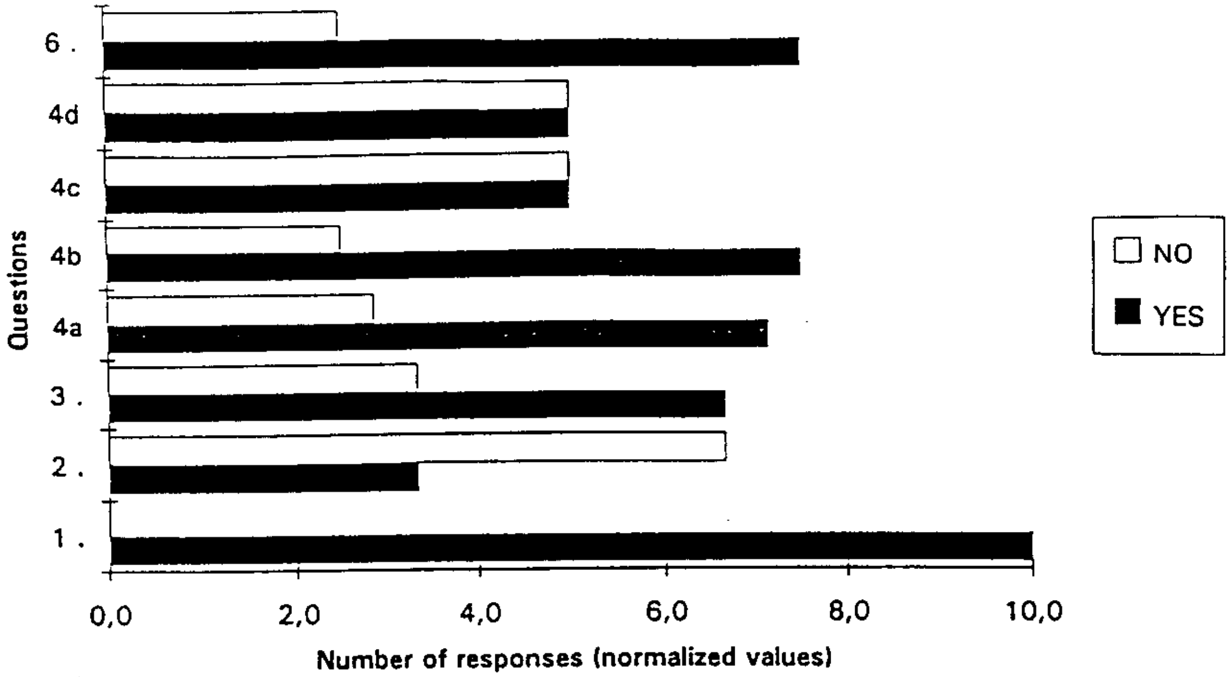

Figure 2.12: Improvement Needs for Transformer Protection Functions.

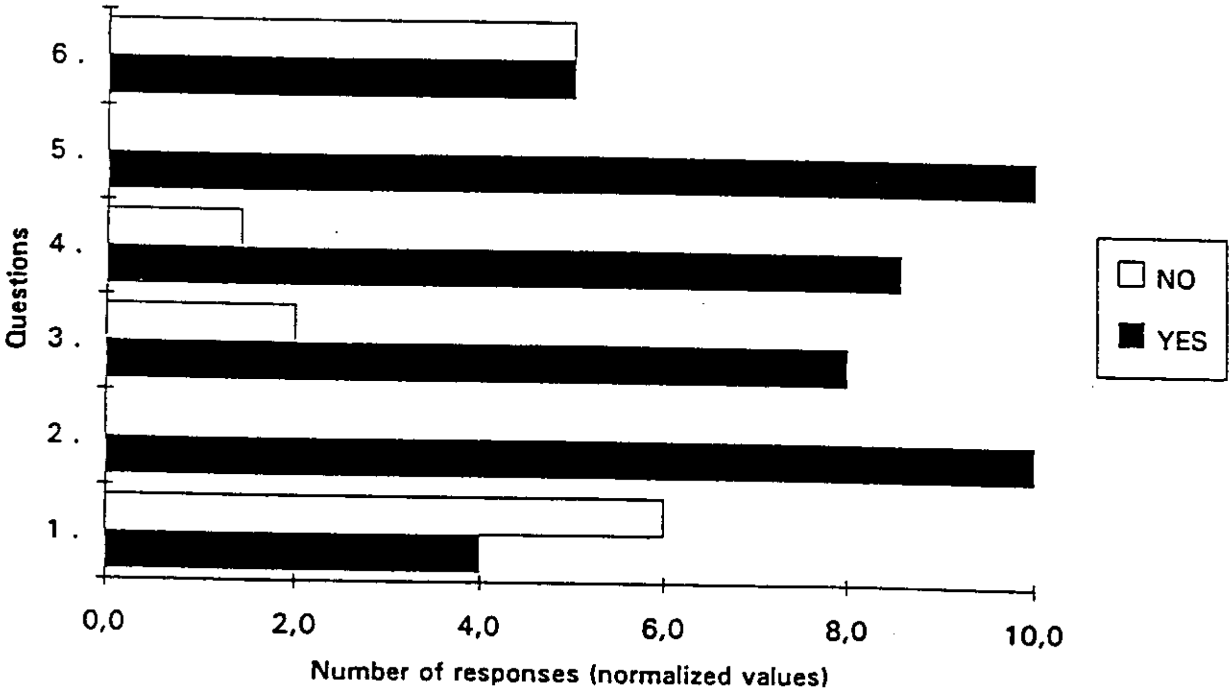

Figure 2.13: Improvement Needs for Bus and Breaker Protection Functions.

<u>2.7.2.4</u> Generators

Need of improvements is claimed in 6 out of 10 cases. No improvement needs are pointed out in cases 3 to 6 (impedance, overcurrent, maximum voltage and min-max frequency relays). See also Figure 2.14. Digital relays are used in all the cases and in 30.3 % of responses.

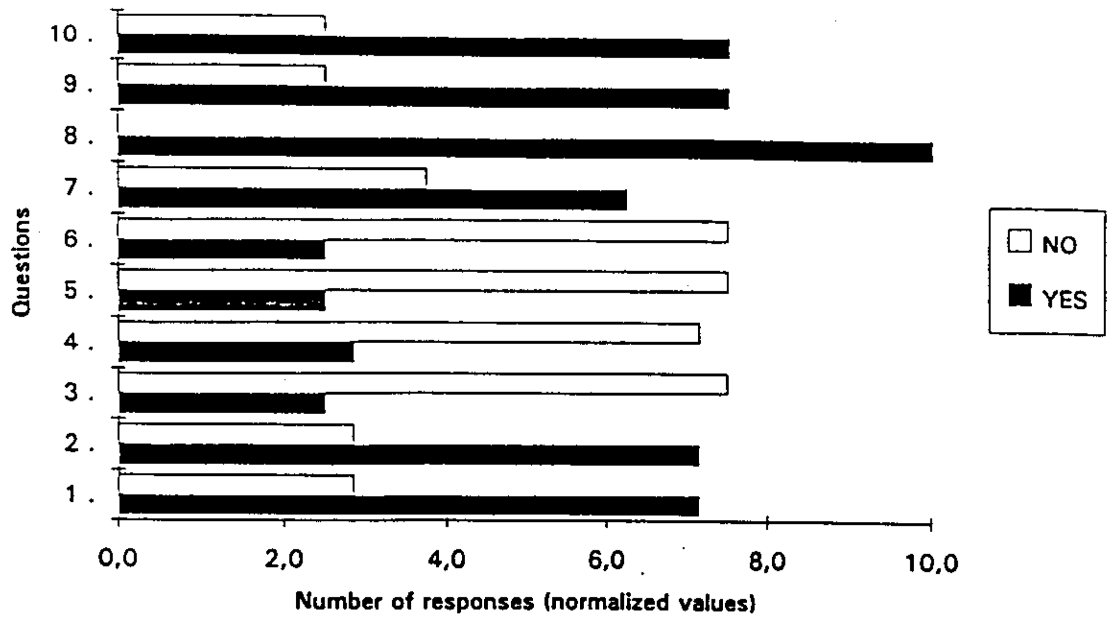

Figure 2.14: Improvement Needs for Generator Protection Functions.

2.7.2.5 Conclusions on protection systems experience

Improvement needs are evident, with a slight exception in case of generator protection, see Figure 2.14. The penetration of digital relays is not quite high, and it is appreciable only in generator protection area. It is perhaps possible to observe that improvement needs are less apparent when digital protection systems are used.

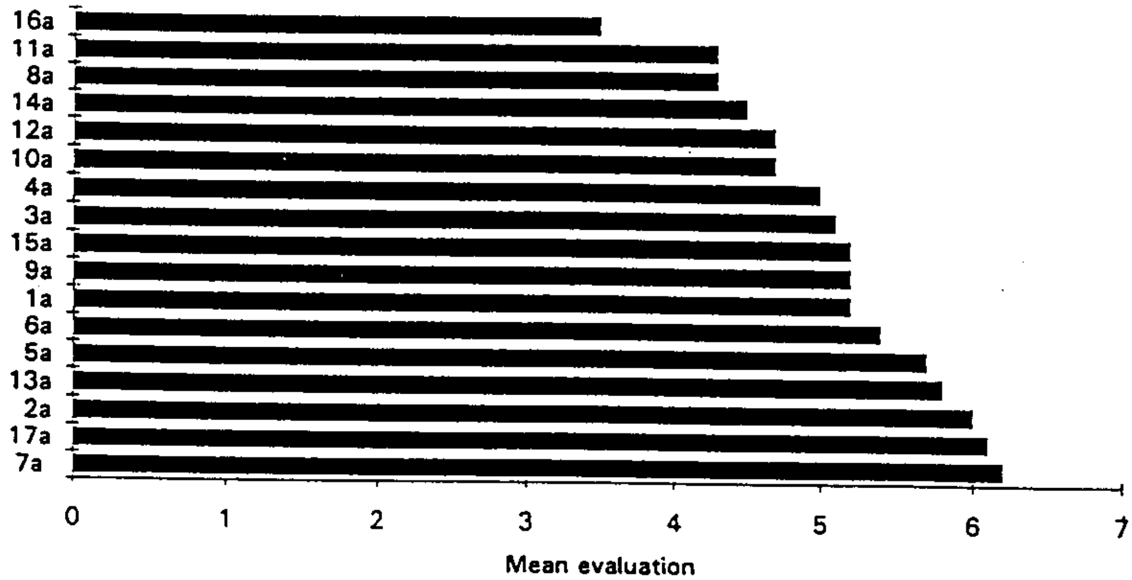

Figure 2.15: Adaptive Protection Topics Evaluation. Ordered by Evaluation Degree.

2.7.3 Adaptive protection possibilities

The mean of responses to the 17 proposed topics is always over the medium (4), with the exception of topic 16, bus protection restraint for arrester applications (see also Figure 2.15).

The topics with best rating (more than 6) are 7 (multi-terminal distance relay), 17 (adaptive protection and control) and 2 (Mutual coupling compensation in ground impedance protection), see Figure 2.15. Figure 2.16 shows the distribution of responses to proposed topics. The categories with the largest number of responses is 'between 5 and 6', with almost half the responses. Responders have also proposed 4 more subjects:

- Overload supervising control system (G01);
- Central system to support operators in emergency conditions (I02);
- Generation control in network splitting and islanding (I03);
- Fast valving in thermal generating stations (I03).

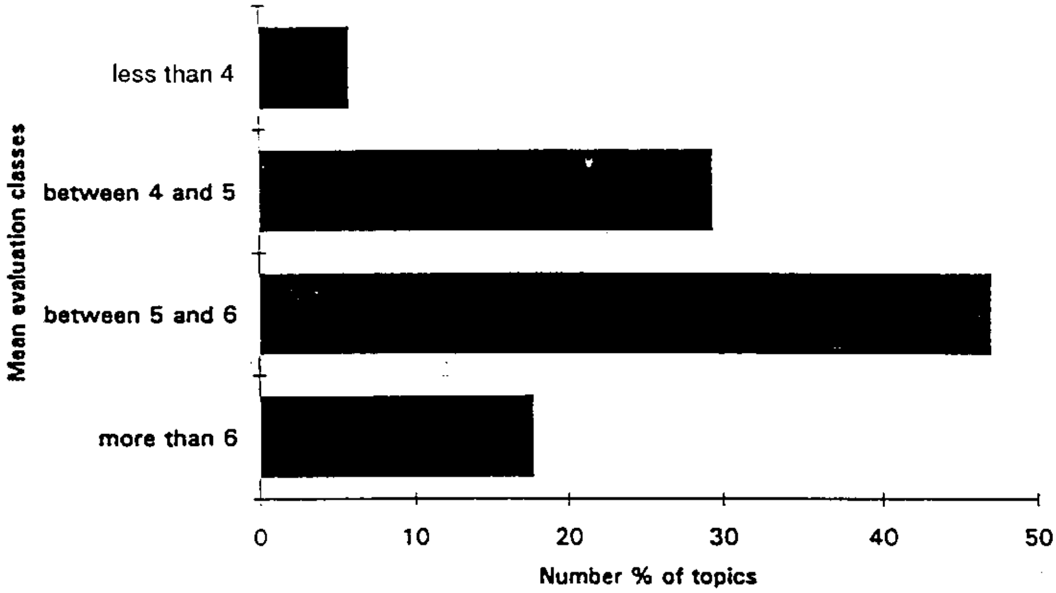

Figure 2.16: Adaptive Protection Topics. Evaluation Distribution.

2.8 Survey results from Nordic Countries

This section gives a summary of the responses to the survey sent to the Nordic countries as well as to some parts of Eastern Europe. The questionnaires were also sent to Russia but no answers were received. The following number of responses have been received from each country:

Sweden	4
Denmark	3
Finland	1
Iceland	1
Hungary	1
Estonia	1
Lithuania	1

Below, the result will be given with one bar graph for each application area. The Index for Improvement Needs is calculated as defined earlier in Section 2.1.1.

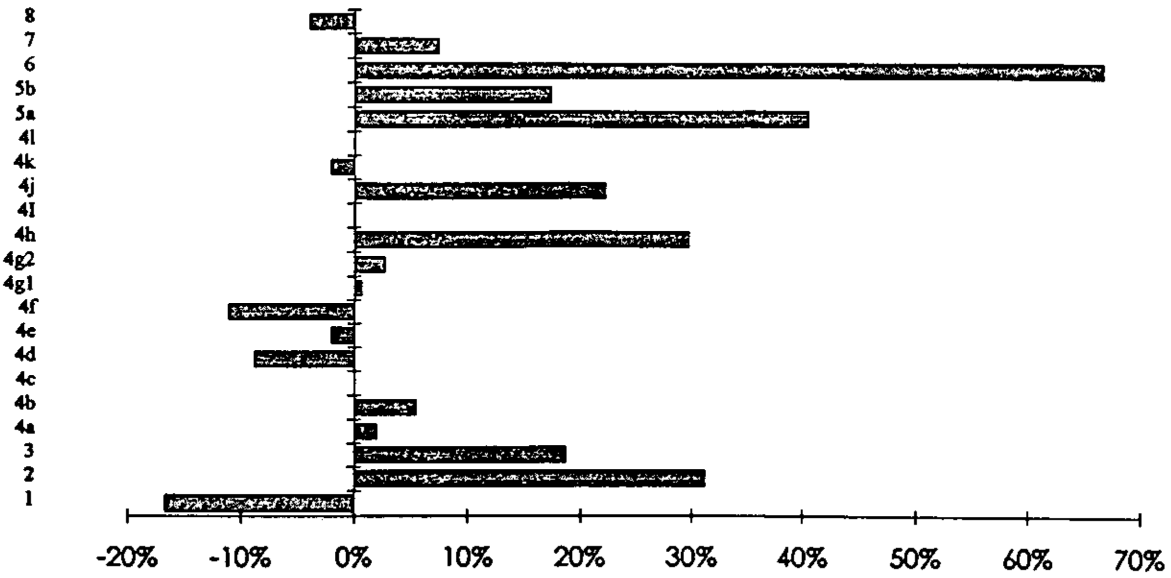

Figure 2.17: Transmission Line Improvement Needs.

In the case of Transmission Line Protection, it is noticed that most improvements are needed for the application of multi-phase trip and reclosing as well as for the application of single-phase high speed trip and reclosing. Both earth-fault distance (2) and current differential protection (4h) also need substantial improvements.

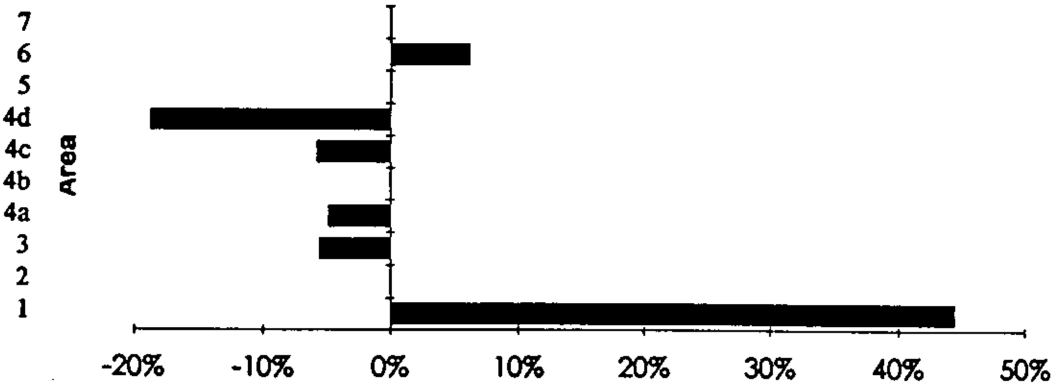

Figure 2.18: Transformer Protection Improvement Needs.

For the case of Transformer Protection, it has been clearly shown that most efforts are needed for the improvement of differential relays principles or algorithms (1).

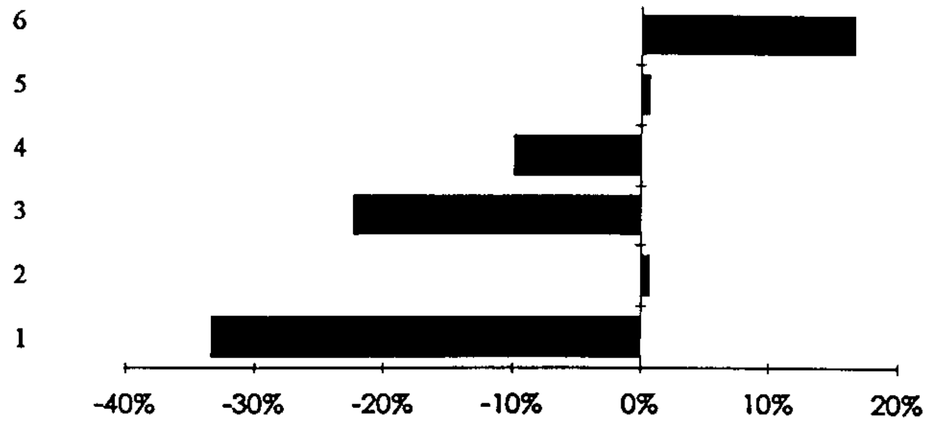

Figure 2.19: Bus and Breaker Improvement Needs.

For the case of bus and breaker protection , the survey show that the existing protections satisfy the needs. However, in the area of breaker failure some improvements are needed (6).

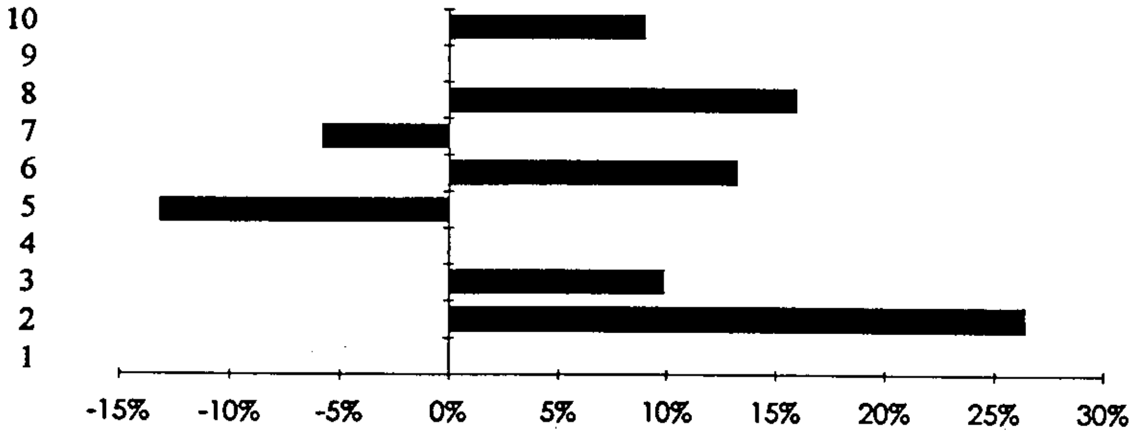

Figure 2.20: Generator Protection Improvement Needs.

For the case of generator protection, the existing protections satisfy the needs to a high degree. However, some improvements are needed in the areas of stator ground fault protection, out-of-step and minimum and maximum frequency protection.

Desirable adaptive features

In this part of the survey, each feature was given a rating between 1 and 7 where 7 is most desirable. The horizontal scale in Figure 2.21 is calculated as the sum for each feature over all responses divided by the number of responses and multiplied by 7.

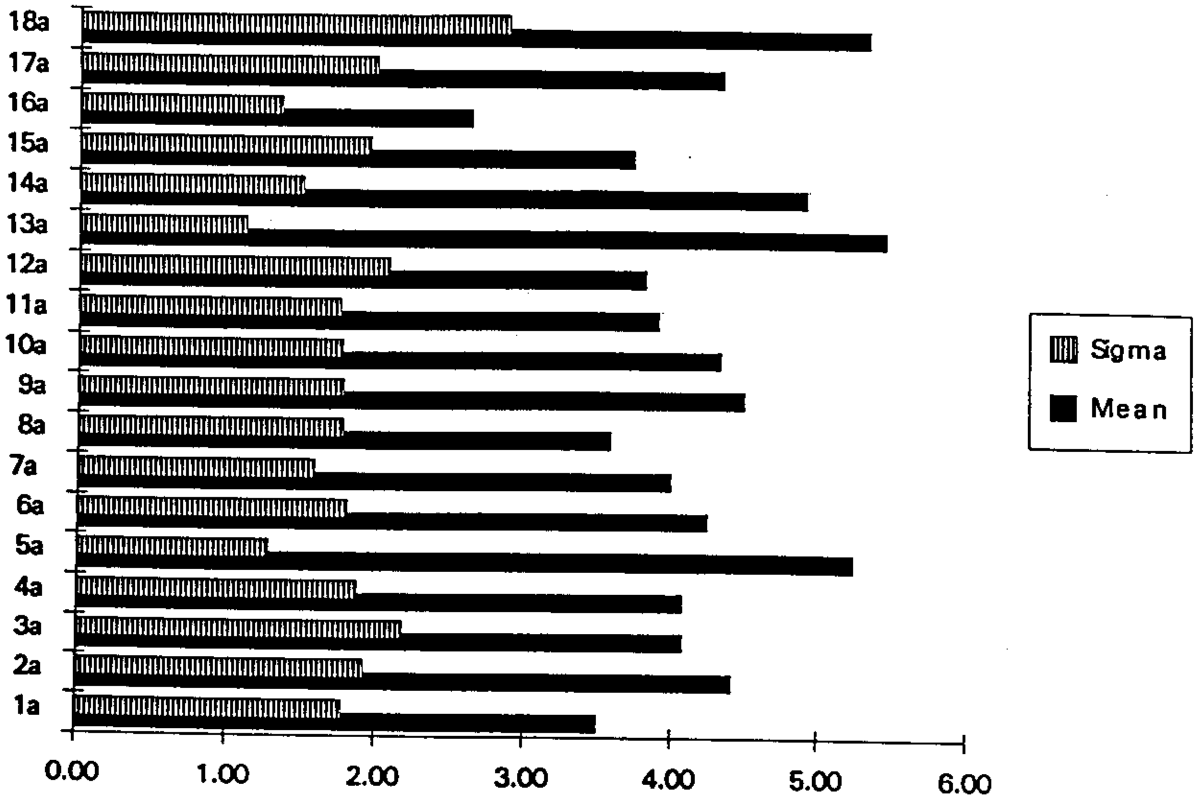

Figure 2.21: Summary of Survey Responses to Section (B) for the Nordic Countries.

It is worthwhile to mention that in the opinion of the responders, in almost all application areas, the implementation of various adaptive features are highly desirable. The application areas of adaptive reclosing , adaptive transformer differential, adaptive load-flow and load-shedding are among the most desirable for the introduction of adaptive features.

Although the responses of this survey are obtained from only few utilities of the respective country, the results shown in various bar graphs clearly define the improvements needed in various application areas of different protection groups.

2.9 Statistical Analysis and Comments on the answers from North America.

Part I - Responder's Particulars

There were only 10 North American responses to this CIGRÉ questionnaire, (6 from Canada, 3 from the United States and from 7 Brazilian utilities, which are not enough to reach statistically meaningful conclusions. There are, however, obvious trends which can be identified and which can be compared to the IEEE Power System Relaying Committee (PSRC) survey. Both surveys verify that there is a great deal of satisfaction with existing equipment. Of the respondents, the American and the Brazilian respondents consistently indicated that a relay needed improvement with an occasional respondent indicating a need for improvement in some less commonly used scheme. This compares favorably with both bar charts of the PSRC survey where the mean of the satisfaction index was predominantly above 5. Similarly, those relays in our present survey that indicated the greatest need for improvement, such as non-segregated pilot wire, non-harmonic restraint transformer differential and pole disagreement also received less favorable evaluations in the previous survey.

The questions involving generator protection were not in the PSRC survey so there can be no comparison. However, the 10 responses from North America clearly show satisfaction with existing relays. Stator ground and out-of-step relays show a relatively minor desire for improvement.

Similarly, the use of digital relays was not included in the previous survey. The responses here indicate that digital relays have found some use in transmission line protection with more extensive use in protection schemes which involve more logic functions such as single-pole tripping and reclosing, volts per hertz and some transformer differential applications and less use in generator protection.

Part II - Adaptive Protection Possibilities

In spite of the general satisfaction with existing relays, there is apparently a strong desire to provide some adaptive capability. From the North American responses, the most popular schemes for which adaptive capability should be provided are:

3 - High Source Impedance Ratio (SIR) Changing
4 - Remote-End Open-Breaker Detection
5 - Load Flow Compensation
17 - Adaptive Protection and Control

all receiving a high rating with mean above 5 out of 7.

The least popular changes related to adaptive protection are:

8 - Variable Breaker Failure Timing
9 - Permissive Reclosing
11 - Sympathy Trip Response
15 - Voltage change Supervision of Differential
16 - Bus Protection Restraint for Arrester Application

3. SOME ADAPTIVE PROTECTION POSSIBILITIES

In this chapter, we collect some examples of protection functions which may benefit from adaptive relaying concepts. Thus of necessity, this chapter is organized as a list of several protection scenarios, without a coherent thread which binds the several discussions in a common narrative. The only common thread is the idea of "adaptive protection" explained in Chapter 1. Each item is discussed briefly to point out the adaptive possibilities in that particular application. Fundamental requirements on communication are mentioned. There is no attempt to put forward a complete blueprint for any of these adaptive protection proposals. The working group recognizes that relay experts would have their own favorite examples of adaptive protection, and we hope to hear about these ideas in discussions of this report, or in future technical communications.

3.1 Adaption of remote Back-up Zones of Distance Protection

To provide optimal back-up protection the zone settings of the distance relay in location A have to be adapted according to the infeed in station B (see Figure 3.1). The distance protection in A can have various sets of settings and the related control unit in B communicates the selection to the relay in A. There are no special requirements on the speed of communication. The adaptation shall be done without interrupting the operation of the protection function.

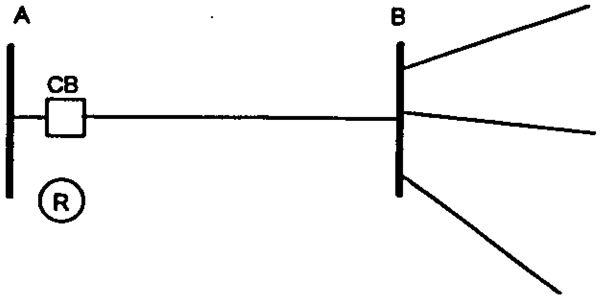

Figure 3.1: Infeed status at remote bus.

3.2 Distance Relay at Transfer Bus

The transfer bus is used to bypass the switchgear of any feeder to make maintenance possible without interrupting the power supply. The distance relay allocated to the circuit breaker at a transfer bus has to protect different lines. Assuming that the distance relay offers facility to pre-store different sets of settings, the selection of settings can be done automatically in connection with the closing of the feeder isolator concerned. (See Figure 3.2) The adaptation can be done while the protection equipment is disconnected, so that no requirement on the speed of change-over of settings need to be specified.

3.3 Transformer Differential Protection during switching of transfer bus

In the case of a transformer feeder when switching over from the feeder circuit breaker to transfer bus (see Figure 3.2 again), during a short but a critical period of time the two circuit breakers are closed and the differential protection has to compare these currents. It would be too risky to block the differential protection during switching periods. Numerical protection makes it possible to switch the differential protection from a two-winding to a three-winding function automatically, without problems of switching secondary currents.

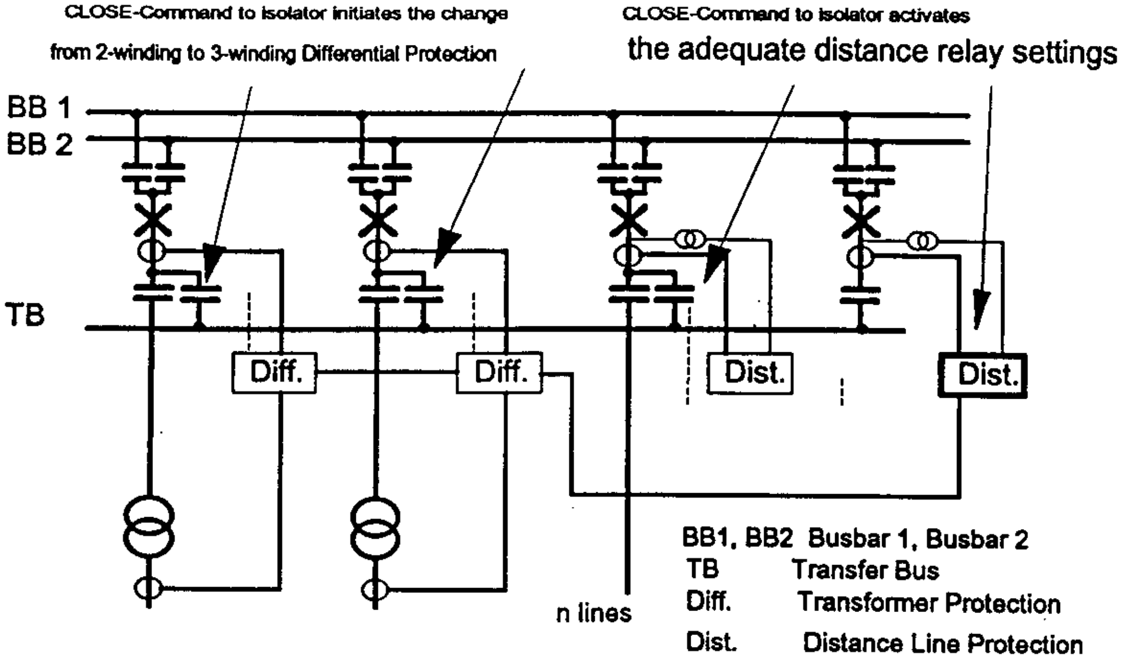

Figure 3.2: Adaptive protection with a transfer bus.

In the switching sequence, the appropriate isolators have to be closed first. There is enough time between isolator operation and circuit breaker closing to initiate and start numerical relays with new configuration and settings. The closing command to circuit breaker is released by a logic 'availability' signal from the numerical protection. The required speed of change-over of functions is the same as in the example 3.2 above.

3.4 Adaption of fault detection level of line protection

During emergency network conditions if one or more important lines have been tripped, there is a need to allow a limited pre-determined overloading of the lines in service. The idea is to adapt the settings of fault detectors and of overload or overcurrent protection to prevent a total blackout.

This application is in accordance with UCPTE [4]. Item 3.4c of this reference states: "If there are changes in operating conditions the settings of the protective devices must be immediately adjusted to suit the new conditions. The protective equipment can where possible also be readjusted by remote control via the network management system". The maximum available time in this case to perform the adaptation will be in the range of a few seconds and the adaptation shall be performed without any interruption of the availability of protection.

3.5 Power swing detection and control

Power swing detection and control by means of out-of-step relays in distance protections is an important task in High Voltage network control. Distance protection should be able to distinguish between stable and unstable swings. The features required for distance protection schemes to operate in "adaptive modes" are (i) to act to block or trip following the detection of stable or unstable swing, and (ii) to accept a remote signal for coordination, sent during normal service conditions without high requirements on the speed of communication.

3.6 Performance of generation protections during fast valving operation

Fast Valving is an important means to improve stability and prevent out-of-step condition in large thermal plants following faults. However, the operation of fast valving can cause the intervention of generator impedance protection, because of the large variations of the apparent impedance during the ensuing transients. The generation protection system should be made aware of the Fast Valving operation to prevent undesired trips. In this case the adaptation must be fast. It shall be faster than the generator impedance protection. Within a power plant it should not be a problem.

3.7 Protection operation during network restoration conditions

In restoration conditions large changes in frequency, voltages, and power flows can occur. It is important that they do not have protection intervention in such a situation. This can be achieved by (i) blocking the intervention of some relays e.g. voltage relays or under-frequency load shedding relays, and (ii) modifying the starting conditions (or fault detection level) of line protections, usually adjusted for normal conditions. This is a system wide task. The success of the action will rely very much on the speed of performing the adaptation.

3.8 Protection operation during network voltage emergency conditions

In network emergency conditions often large voltage decreases (or even voltage instability situations) occur. To avoid relay operation during this emergency condition, the relay settings must be modified during conditions of this nature. The requirements on the speed are similar to those in 3.7.

3.9 Mutual compensation on parallel lines

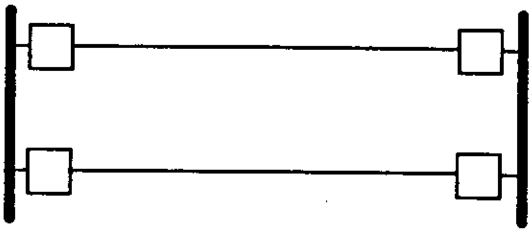

Figure 3.3: Distance protection of Parallel lines bussed at both ends.

Distance protections for parallel lines ending at the same busbar (see Figure 3.3) without mutual compensation exhibit tendency to (i) underreach when both lines are in service and (ii) overreach when a parallel line is switched-off and earthed at both ends. A similar situation occurs in partial parallel lines (see Figure 3.4) [5]. A careful application of mutual compensation for zero sequence can solve this problem. The adaptive approach consists mainly in informing each relay about the status (in service, switched off, terminals earthing) of the parallel lines.

The most common problems concerning distance protection of parallel lines ending at the same busbars can be summarized as follows:

Units without mutual compensation exhibit a tendency to:

1. Underreach when both lines are in service.
2. Overreach when the parallel line is switched-off and earthed at both ends.

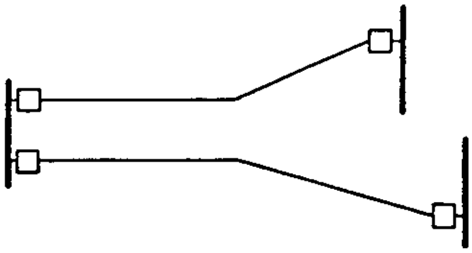

Figure 3.4: Distance protection of parallel lines bussed at one end.

Sometimes it is difficult to find a setting that ensures a minimum of overlap with the setting the remote unit (at least 50% of line length plus a safety margin) without selectivity problems (tripping beyond remote terminal).

On the other hand, mutual compensation for zero sequence current in the parallel line is not often used, mainly because of two problems:

1. Tendency of false tripping of the healthy line during earth faults in the parallel line;
2. Also a tendency to overreach when the parallel line is switched-off and earthed at both terminals because, in this case, the parallel line current is not generally available.

Techniques that could allow a more widespread use of mutually compensated distance relays are as follows:

- Problem (1) above has been overcome usually by comparing the magnitude of the zero sequence currents in both lines and performing the compensation only in that line where the zero sequence current is higher (by a certain amount) than that of the parallel line.
- Another possibility is to block the output of the mutually compensated unit by the instantaneous output of a non-compensated overreaching unit. Preferably the underreaching and the overreaching units should use the same input signals and algorithm so as to ensure a faster operation of the overreaching unit (provided by the bigger reach).
- Problem (2) above can be overcome using an *adaptive* approach: If the relay is informed that the parallel line is earthed at both terminals its earth compensation factor can be switched to another value that would take into account the new situation.

3.10 Real time stabilizing protection

Power system instability can be detected by means of real time calculations based on data processed locally or remotely. Depending on such detection, control actions, such as load or generation shedding, system separation, etc. can be actuated. This principle has been incorporated in an adaptive out-of-step relaying system [6].

3.11 On line stability protection

If on line dynamic security analysis is performed in a power system Energy Management System (EMS), it is possible to know the control actions necessary to solve a set of expected problems. An appropriate relay can initiate such actions when one of the previously analyzed disturbances occurs.

3.12 Adaptive conversion of protection schemes in cases of partial protection system failures

An example of this application is an n-terminal differential protection, if data from one terminal are lost due to protection system failures (including telecommunication failures), the protection is converted into distance protection or overcurrent protection for the (n-1) terminals. This feature minimizes deterioration of the protection capability under partial protection system failures.

3.14 Voltage change supervision of harmonic restraint

During faults on power systems adjoining High Voltage Direct Current (HVDC) systems, Thyristor Controlled Static Capacitors (TCSC) or large power cable networks, there is a possibility that protection with harmonic restraint, such as transformer differential protection or zero sequence overcurrent protection taking into account effects of a magnetic storm, may fail to trip due to distorted fault currents having low second harmonic components. Step changes in the applied voltage of the protected segment can be used to block the harmonic restraint of the protection in such cases. The speed of the adaptation is not very time-critical.

3.15 Adaptation to changing earthing conditions

Distribution/transmission networks in the range of 50 to 150 kV very often have various earthing conditions during service. As an example a low-impedance grounded network may be isolated for a while during switching in the network, the number of earthing points - and with that the earth fault current may change under the same conditions. The same may happen to an inductively grounded (compensated) network, the neutral suddenly being isolated.

The directional earth-fault protection should have different characteristic angles and sensitivities according to the different earthing conditions - or in other words, according to the topology.

With an information system comprising the overall network, the topology and with that the earthing conditions can be monitored and the protection adapted with respect to characteristic angle and sensitivity. The same information can be used to keep the earth fault current below a certain limit by switching the grounded transformers accordingly. Alternatively additional earthing resistances in the neutral of an inductive grounded network during earth fault can be connected.

With this method the network topology will be changed to keep earth fault currents in the required range and at the same time and with the same information the protection functions will be adapted to the actual earthing situation in sensitivity and measuring characteristic. Low-impedance grounded networks with these additional features are under consideration. The block diagram of the provided solution is shown on Figure 3.5. The necessary information has to be updated in about once per second. The adaptation has to be done during service conditions but has to be communicated from the network control center to different stations and relays. Availability and reliability of communication is more important than its speed.

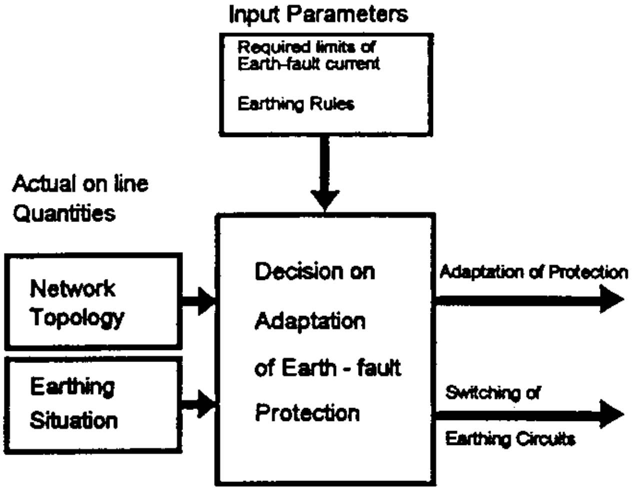

Figure 3.5: Block diagram of adaptive earth-fault treatment.

3.16 Voltage protection with variable voltage reference

Voltage protection schemes are generally set as a function of the nominal voltage. This setting is fixed by the VT but the real network voltage could differ from the nominal voltage as a result of tap position, load and system operating regulations. Therefore it would be interesting to have a voltage protection scheme that is a function of a variable voltage reference (prevailing voltage) instead of the nominal voltage. If a small change in voltage occurs for a considerable time (some seconds) the voltage reference should be adapted, otherwise the protection should continue to work normally.

3.17 Non-linear impedance-distance relation for cable networks

More and more cables are used in the network. With modern single-core polythene-insulated cables and depending on the earthing points of those cables, there is a non-linear evolution of impedance with distance. It would be interesting to be able to define the non-linear curves (for example by different linear sections) in order to obtain better selectivity. The same protection principle could be applied to mixed cable-overhead line sections.

4. TECHNICAL ASPECTS OF ADAPTIVE PROTECTION SYSTEMS

This chapter will discuss some aspects of technologies which can be used for the implementation of an adaptive protection system. The evaluation is based on the requirements which are set up by the previously established definition of adaptive protection.

4.1 Tasks within the adaptive system

The adaptive subsystem of a generic adaptive protection scheme as introduced earlier, can operate according to two different main principles:

Type A: In this case information is collected in the adaptive subsystem and is fed into one or more of the main blocks of the protection system. This is ***continuous*** adaptive operation. In order to facilitate a safe fall back position, default values of the information can always be used if the communication system fails.

Type B: In this case, the protection system may be altered between a number of predefined states or conditions depending on the power system mode of operation. These adaptive systems use a ***state identification*** as an operating tool of the adaptive protection system.

4.1.1 Type A - Continuous Operation

The continuous operation of an adaptive protection scheme is rather straight forward. The adaptive settings are simply a function of some input data which may be collected either locally or remotely in the power system.

Considering both local and remote information as a general case, the local information is a vector L(t) and the remote information is a vector R(t). The adaptive settings are a vector S(t) which is a function Γ of the input data:

$$S(t) = \Gamma\,[\,L(t)\,,\,R(t)\,]$$

To facilitate a safe fall back position in case of a communication failure a plausibility check have to be added. Thus,

$$\begin{aligned} S(t) &= \Gamma\,[\,L(t)\,,\,R(t)\,] \qquad && \text{if } L(t) \in \Lambda \text{ and } R(t) \in X \\ S(t) &= S_0 && \text{else} \end{aligned}$$

where Λ and X are the possible sets of input signals and S_0 is the default setting vector which is used if the adaptive features can not be applied. The determination of the adoption function varies from application to application and has to be done individually. Of course this function has to be determined so that its computational requirements and speed match with the specific application of the adaptive protection.

It is possible to use more novel approaches such as fuzzy logic, neural networks etc. in the signal processing in the adaptive function. However, a problem related to this is that it may not be possible to predict the output of the function with high confidence in all situations which means it will be extremely hard to do any systematic test on the system.

4.1.2 Type B - State Identification

The state identification type of adaptive protection or control scheme can easily be broken down into two sub-tasks. These are identification and activation of new settings, schemes etc. It is important to note that it is mainly the state identification which is a critical task. When this has been carried out, the activation or the altering of the settings is usually easy to determine and can be done following a pre-defined schedule. The pre-defined settings make the system deterministic and possible to test with a definite number of test cases.

State identification

In the case of state identification, information is taken either from the normal signals which are used in the protection system or from some auxiliary signals which are transferred from a remote location. These signals together form a state space which is used to identify different situation when the protection system has to be adopted.

In a three dimensional state space the state identification can be represented as in the Figure 4.1 where two states are identified.

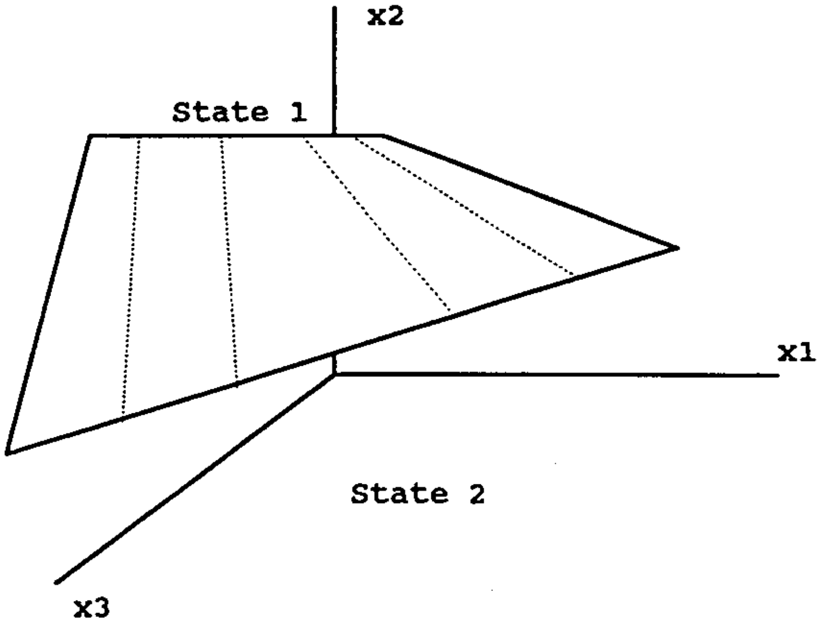

Figure 4.1: State identification in a three dimensional space.

State1 and state2 represent different operating conditions in the power system. When the specific state has been found, the activation of new settings may start.

Activation of actions

Given a specific state the activation of different settings or schemes are done as in a Type A system. The changes can be made to any of the three generic parts of a protection system, i.e. signal processing, fault detection or logic.

Given state i, the adaptive setting is selected as:

$$S = S_i$$

It is possible to make a system in which the changes to the protection system are not determined beforehand. However, such a system would be very hard to test and verify and it is therefore questionable if such a system may be used in practice.

4.2 Available technologies

This section will describe a number of different technologies which may be used for the implementation of adaptive schemes described in the previous sections. It is important to note that this type of overview can never be complete, there will always be other alternatives.

The most important features of adaptive relaying include normal methods for numerical protection. These will play an important role also in the implementation of adaptive protection systems. Among these features are digital filtering, identification, parameter estimation, etc. It is important to point out that the adaptive features will be implemented by the new adaptive structure of the protection system, rather than through the use of novel technologies. However, for some specific tasks, a new technology may play an important role. For example, such tasks are modeling in the presence of uncertainties, filtering in a noisy environment, or complex decision making with a large number of boundary conditions. Implementation of the adaptive features will require input data selection, on-line relay setting and characteristic modifications, and finally the anticipated relay action.

As described in Chapter 1, an adaptive protection system will need auxiliary information to properly adjust the relay setting or characteristics to prevailing power system conditions. The volume of the data (auxiliary information) will be dependent upon its functional requirements in a power system. The data, or the auxiliary information, are supplied based on the needs of the protective scheme and can vary significantly from one application to another. Additionally, selection of communication channels and protocols will require proper attention, since the relay input data requirement might not be restricted to the local information.

Modification of the relay setting and characteristics based on this input data will necessitate a systematic approach. A first approach in providing system-scale information is to implement some well assessed network analysis techniques (Transient Energy Function method, fast short circuit calculation, etc.) in digital protection or in EMS functions connected to protection. A further approach is to consider innovative techniques. Artificial intelligence (AI) techniques may provide a solution to accomplishing this goal. Artificial intelligence programs can operate on the data according to rules for automatically permitting and seeking the necessary adjustments of complex relaying functions. As AI technology matures, it will become easier and more efficient to exploit its capability, and allow many data processing and decision-making steps to be performed by the AI methodologies. The AI rules which are the properties of the engineering knowledge, design experience, and the accumulated wisdom of the power protection profession are exercised to make the determination of the proper relay actions. The relay actions may be local breaker or remote breaker action. As higher level power system control and protection become inseparable, the relay action might not be restricted to a discrete action such as opening a breaker, but it might involve control functions such as adjustment of generator excitation system reference voltage, HVDC and SVC set-points, etc.

The relevancy of AI technologies should be considered for adaption of a relay to system changes. Several variations of the AI methodology are available:

- Production Systems
- Fuzzy Logic

- Abduction
- Induction
- Model Based Reasoning
- Qualitative Physics
- Neural Networks/Perceptrons
- Case-Based Reasoning
- Meta-Control
- Expert Systems

The ability and level of maturity of each individual AI methodology should be assessed. Elements in assessment of each method should include: risk, reliability, ease of implementation, speed, economics, adaptability, etc. The most promising methods should be identified and further pursued. Some technologies which may be used for adaptive protection tasks are: expert systems, fuzzy logic, artificial and neural networks.

Table 4.1 combines the AI type of implementation technology with more traditional methods. It indicates which technologies can be used or are best suited for which types of adaptive protections.

Technology	**Type A-Cont.**	**Type B-State ID**	**Type B-Action**
Communication	Yes	Yes	Yes
Traditional numerical methods	Yes	Yes	Yes
Expert Systems (rule based)		Yes	
Fuzzy Logic	Yes	Yes	
Artificial Neural Networks	Yes	Yes	
Pattern Recognition		Yes	

Table 4.1: AI technologies for adaptive protection.

4.2.1 Communication

As mentioned earlier, communication systems of various types are essential to get information into the adaptive protection system in order to facilitate the state identification. The communication may include communication with an adjacent bay within the same station, with the corresponding line end in another station or even with the remote control center.

In order to be able to build-up different adaptive protection and control systems, horizontal and vertical integration are very important. Horizontal integration means that a specific system in a substation has to be integrated via the communication system to a neighboring system in the same or another substation.

Vertical integration means that a system in a substation is integrated with systems in the Regional Control Center or National Control Center by means of communication links. This integration means more than just setting the system from the control center. The two situations are illustrated in Figure 4.2.

By means of horizontal as well as vertical integration, systems can easily be made adaptive by adding more information. Well established standards are important to facilitate this type of integration. However, it is extremely important that the standards are a subset of the seven layer OSI model. In the current situation when adaptive schemes are to be introduced, no one can exactly describe the type of information which is going to be exchanged between different applications. Hence, communication standards (such as the DIN VDEW6) are not well suited for utilization in an adaptive protection system.

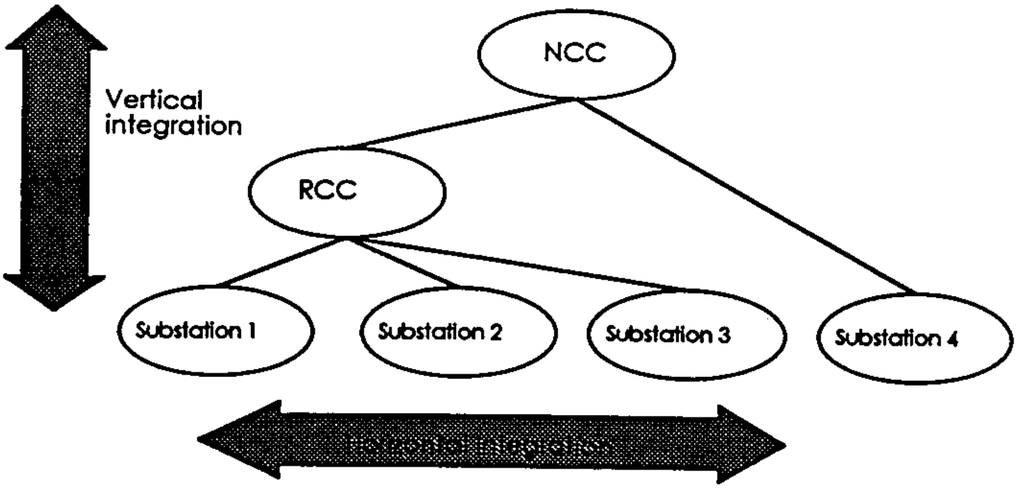

Figure 4.2: Vertical and horizontal integration.

The general trend within communication technologies is rather towards standard field busses like ISP and general computer networks like TCP/IP which are based on the Ethernet standard. In the future the area of adaptive protection as well as the rest of the power system protection and control area will be influenced by the development of electronic super high-ways and Internet. It will be possible to communicate information to any location with bandwidths which are more than enough to communicate instantaneous samples of the power system voltages and currents.

Although the communication systems of today have rather limited speed, adaptive protections can be implemented because of relatively low speed requirements, which correspond to the slow dynamics of the power system.

4.2.2 Traditional numerical methods

Normal signal processing of digital sampled signal may be used in adaptive systems. There is no basic difference between how to implement the adaptive system or the rest of the protection system. The signal processing is carried out in either general purpose CPUs or in special DSPs (Digital Signal Processors).

4.2.3 Expert Systems [7]

Expert Systems (ES) is a technology that uses rules (knowledge) instead of a sequential computation program to solve problems. The kernel of an ES is formed by the knowledge base, that contains the knowledge in the form of coherent IF-THEN rules, and an inference engine, which searches for the right rules to be applied depending on the offered information. The idea of an ES is that some problems have to be solved by reasoning rather than by computation. The general structure of an ES is shown in Figure 4.3.

The user or the process communicate with the ES via the *"natural language interface"*. The information is put into the ES via the *"explanation facility"*, that forms the input for the *"inference engine"*. The inference engine combines the information from the user, the process and the *"knowledge base"*. The conclusions (output) of the inference engine is fed back to the user or the process. The knowledge base is built up by information from the expert. External routines and external data bases support this scheme with extra information.

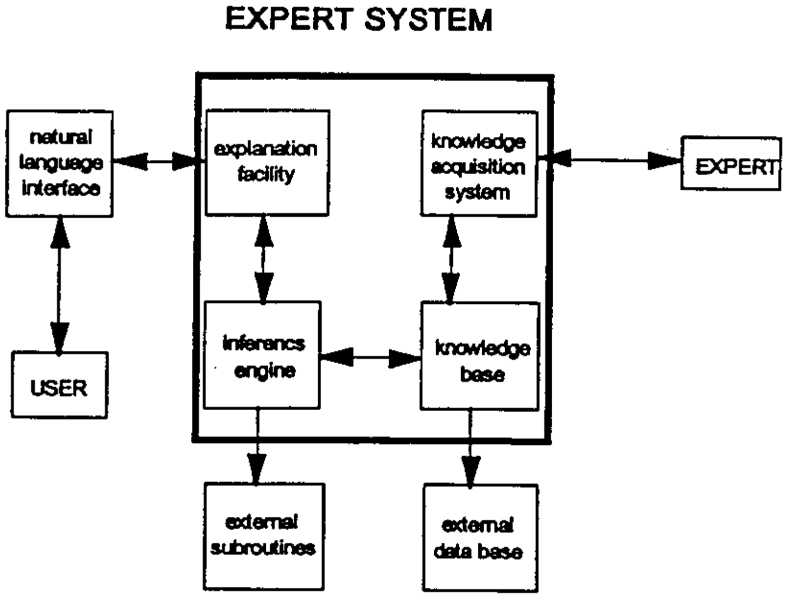

Figure 4.3: General Structure of an Expert System.

Expert Systems were developed to substitute for experts, whose knowledge was not always accessible. Illness and retiring of experienced people caused inconsistency and loss of experiences. The idea was to gather the knowledge of the experts in ES, and use these systems to educate future experts and replace existing experts.

Advantages of this approach were the independence of the presence and state of the expert, the consequent behavior of the ES, and a method of tracing the conclusions. A computer will do its work almost any time and any place without asking for pays and overtime, while an expert works "from-nine-to-five". The working of the ES is reproducible, while an expert uses feelings and intuition. Above all, a logging system makes its possible to trace the conclusions and detect failures and gaps in the knowledge-base.

The greatest disadvantage of an ES is the limitation of the knowledge-base. It is almost impossible to extract all the knowledge from experts and transform it into rules that can be used by the ES. Moreover, gaps in the knowledge are very difficult to detect in advance, and the maintenance of the knowledge-base leads to redundancy, overlaps and loss of the overall picture. Besides, an ES has difficulties with reasoning under uncertainty.

Expert Systems can be applied in three areas:

1. education: the knowledge of experts can be applied in training facilities.
2. operation support: the expert is supported by a system that gathers the experiences of himself and his colleagues.

3. modeling and control of simple systems: small systems can be modeled and controlled. The size of the system is limited, and the knowledge can easily be completed.

4.2.4. Fuzzy Logic[8]

Expert Systems have difficulties with reasoning under uncertainties. Fuzzy Logic (FL) tries to solve this problem.

The idea of FL is that a large number of quantities can only be described in a qualitative way: a report is thick or thin, but is very difficult to relate these words to the number of pages. FL solves this problem by defining membership functions. An example is given in Figure 4.4. A report containing 20 pages is **NOT THICK**, a report containing 100 pages is **THICK**. The number of pages in between results in a vague expression: the report is **PARTLY THICK**.

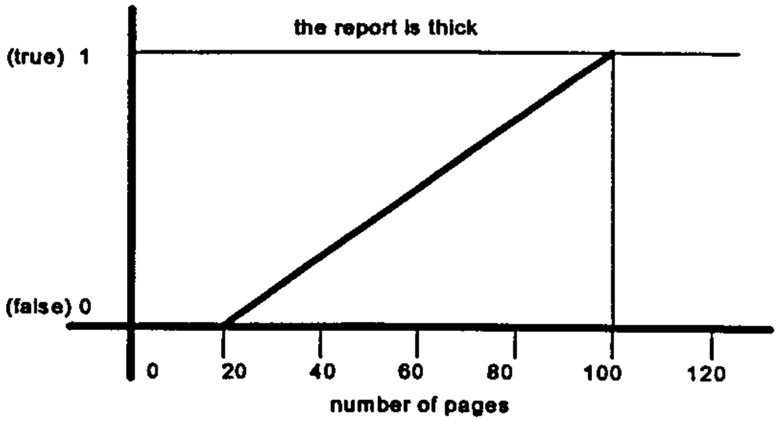

Figure 4.4: An example of a membership function.

This expression is logically combined with other information. An example is given in Figure 4.5. A thick report with high paper quality is expensive; a thin book with low paper quality is cheap. How expensive is a report of 80 pages, with medium paper quality? The answer comes from the fuzzy logic: $ 75.

Fuzzy Logic is developed as an extension to the Boolean Logic. With FL, quantities can be used that are very difficult to quantify. In this way, uncertainties can be modeled. This is the most remarkable advantage of Fuzzy Logic. Vague quantities can be worked with, and the conclusions come in forms such as "partly", "much", "little". Disadvantages of FL are the same as Expert Systems: it is very difficult to create a complete knowledge base, the knowledge has to be explicit, and the maintenance of the knowledge base is a complex problem. The main application area of Fuzzy Logic is adaptive control. A large number of control problems are dependent on the environment of the system to be controlled. FL can take care of the changing environment.

4.2.5 Artificial Neural Networks [9]

A main feature of the human brain is learning. Human beings learn most features by looking carefully at examples. The information that is distilled from these examples are stored into the memory, and it is recalled in an associative way, rather than in an abstract way.

Artificial Neural Networks (ANN) are developed to model and simulate the human learning process. The idea of an ANN is to expose a system to a number of examples, that come from the system to be modeled. After a period of time the ANN has learned the examples. After the learning period the ANN is capable of recognizing examples that it has never seen before. The learning of an ANN is comparable to the setting of a large number of parameters. The setting is executed by a learning algorithm.

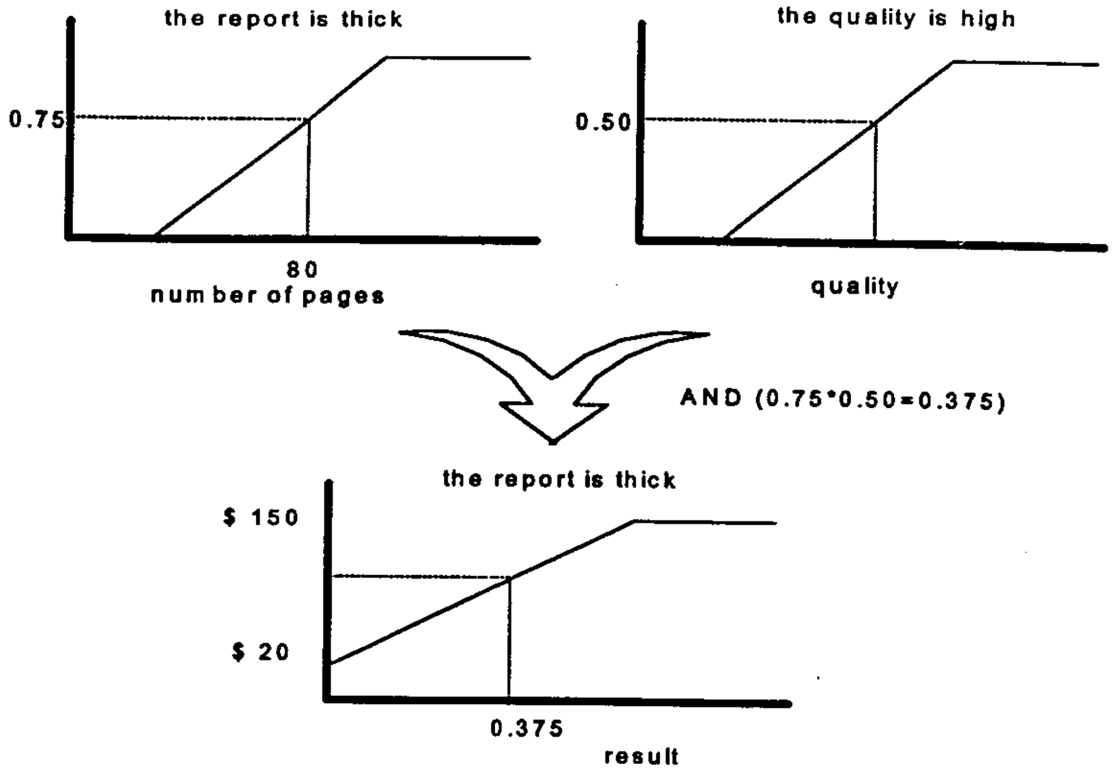

Figure 4.5: An example of fuzzy reasoning.

An enormous number of different types of ANN exists. The Multi-Layer Perceptron (or Back Propagation Network) is the most used one (see Figure 4.6). A well-known network is the Kohonen Feature Map (or Self Organizing Map). Other examples are the Boltzmann Machine, the Hopfield network and Adaptive Resonance Theory.

The advantage of applying ANN is the "learning-by-example" feature. An ANN is not programmed by explicit formulas or rules, but it extracts its knowledge from the examples. In addition, an ANN can easily be used in an non-linear way. It can handle many inputs and outputs at the same time. ANN are therefore very well suited to complex, non-linear problems. The most significant disadvantage is that an ANN performs knowledge extraction on its own. It is (almost) impossible to check the features that have been learned. The only check must be done in a statistical way. The presence of an ANN-expert is (still) necessary to prevent the ANN learning from being stuck at a local minimum.

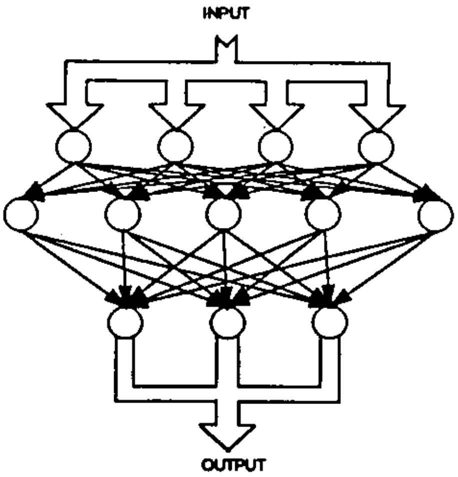

Figure 4.6: A Multi Layer Perception.

•Properties of Artificial Neural Networks are:

- learning from examples
- non-linear
- multi input/multi output
- automatic clustering
- minimization

•Artificial neural networks have their applications in the following areas:

- complex, non-linear modeling
- classification
- non-linear control
- adaptive control
- optimization
- restoration of signals

4.4.5 Pattern recognition

Pattern recognition is a method which can be used to classify a state in a process like the power system process. First a feature vector has to be found in a way that the system state is observable (see Figure 4.7). When this is found, a number of test cases are mapped into the state space of the feature vector and a discrimination function in the state space is determined. This determination is the critical step in pattern recognition and several methods are available. The accuracy of the method is also very dependent on how many test cases are used. The greater the number of cases, the better is the accuracy of pattern recognition process.

The pattern recognition approach as well as the fuzzy logic approach is best suited for a system or a part of a system which can not be modeled, or is a very complex mathematical model. If a mathematical model can be developed, this is always a better alternative.

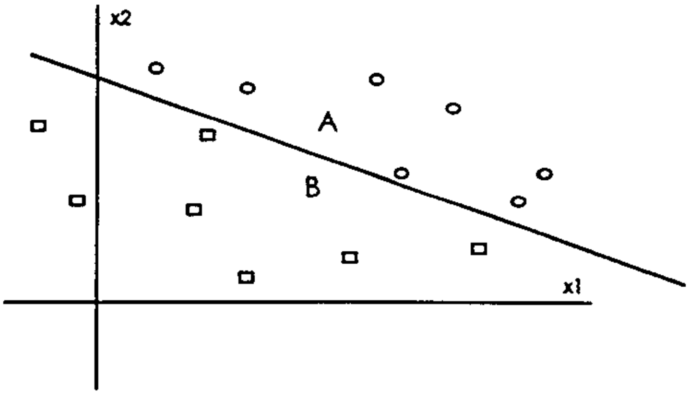

Figure 4.7: Pattern Recognition .

4.3 Examples

The following section will show how the above described technologies can be used for implementing two typical adaptive protection schemes.

4.3.1 Distance protection with source impedance adaption

In normal distance protection systems the source impedance can either be set while commissioning the system or is assumed to have a certain value. The source impedance at a specific location in the network can vary considerably. In general, it is clear that if the source impedance is known with good accuracy, distance protection can be made more accurate. Therefore, it is attractive to apply an adaptive protection scheme to this problem.

This is a representative type A scheme which is working continuously with information which is transferred from the control center to the protection system (see Figure 4.8).

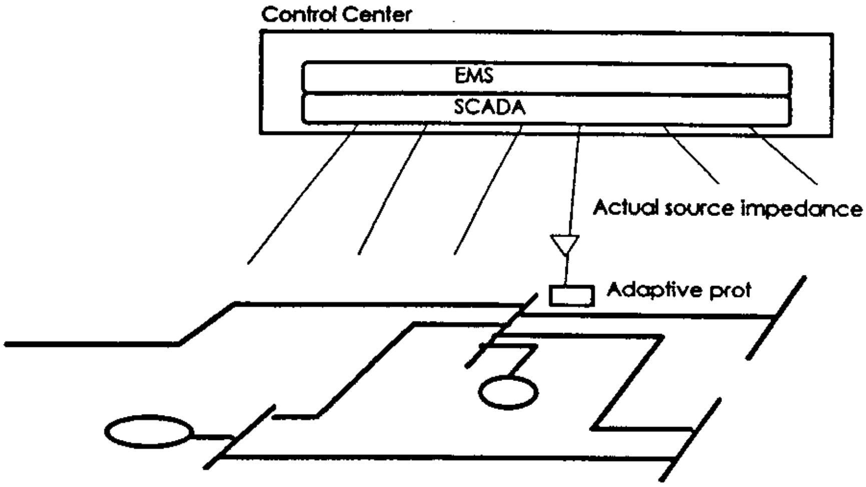

Figure 4.8: Adaptive protection with communication to CC .

The implementation can be carried out by normal numerical calculation methods. No state identification is required and hence no novel classification technology is needed.

4.3.2 Security / dependability adaptive protection

A protection scheme which is adaptive in prioritizing between security and dependability have been described in [16]. This reference describes one way of focusing either on security or dependability. However, there are many more ways in which this can be done in all three main parts of a generic protection system.

A secure protection system is needed in a power system which must be kept interconnected during an emergency situation. A typical situation is when there are active power deficits in the network but the power transfer is relatively low. Dependable operation, on the other hand, is needed in a system which can not stand long fault times due to stability limitations. This means that the power transfer is relatively high.

This is a typical type B adaptive protection scheme. The power frequency and one or many active power flows can be used to set up a state space (see Figure 4.9).

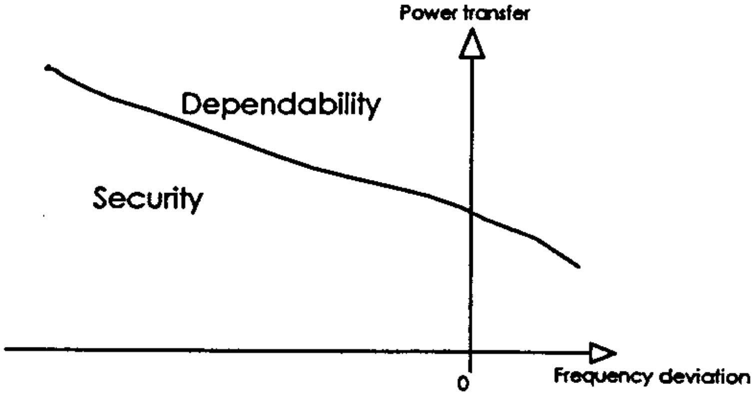

Figure 4.9: Discrimination between Security and Dependability.

The state identification can be implemented with any of the technologies which have been described above.

5. FAILURE MODES AND RECOVERY MECHANISMS

5.1 General

Adaptive algorithms will, by definition, increase the degree of complexity of a protection system. This increase takes place inside the protection due to the existence of algorithms for automatic adaption, and also outside the protection because of the need of decisive information. It consequently creates failure modes which did not exist in non-adaptive protection. Is it worthwhile to take this risk? This can of course not be answered in a straightforward manner. It depends heavily on the application and also on the recovery systems linked with the failure modes.

5.2 Case Study

This case study is performed on a function of medium complexity, but one that exists already in most of the new digital protections: adaption of the setting group as a function of external conditions, as shown in figure 5.1.

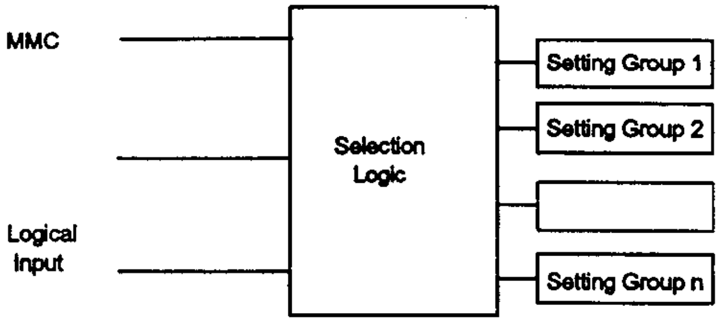

Figure 5.1: Protection with different setting groups.

The system works as follows: the protection has several groups of (complete) settings which can be altered from outside the relay through binary input contacts or via modem communication ports such as RS232 or optical inputs.

Two types of settings can be identified:

a) those where changing settings takes time and is not allowed during dynamical network conditions, e.g. during faults. Sometimes the adaption can only be done through Man Machine Interface (MMI).

b) those where the change is very fast and where precautions are taken to allow dynamic change.

The information for adapting can come from different places, local or remote, depending on the application. For example:

a) from a parallel line
b) from a remote protection
c) from a remote switch or breaker
d) from a control center

It has to be noticed that a time delay between change of network state and indication received at the relay site will always exist.

Adapting settings as a function of external conditions is fundamentally not new. For example, all teleprotection schemes existing in older relays are based on adapting a setting as a function of external information. The difference in what will be studied hereafter is that it concerns a setting group and that more than one choice is possible.

If we analyze the adaptive system we can detect different specific components:

a) the demand for adaption
b) existence of boundary conditions
c) existence of data for adaptive states
d) the processing of the demand

Each of these parts creates different failure modes:

a) the demand is incorrect
b) several demands exist at the same moment
c) time domain boundaries on demand
d) the data corresponding to an adaptive state are wrong
e) processing traps
f) failures that disturb processing

5.2.1 Failure modes and recovery systems

5.2.1.1 Incorrect demand

In the example of switching to another setting group the demand always comes from outside. The communicated message as well as the communicated link can be corrupted. In those cases the setting prevailing at a certain time will not correspond to the reality of the network at the same moment. This can lead to a decrease in dependability or security.

Examples of a loss of dependability: An incorrect signaling on a 3-terminal line that the breaker at a strong infeed end is open will probably adjust the protection setting to lower values and give a risk of delayed tripping.

Example of a loss of security problem: A lack of signaling on the same 3-terminal line that the breaker is open will maintain a setting taking into account infeed and create a risk of unwanted tripping due to overreach.

What can be done against these reliability risks? Suppose we have an application where we can find compatible settings for both conditions. But of course, in that case, we do not need an adaptive relay. When common settings are not possible a classical protection will always work in a decreased security or a decreased dependability mode. The adaptive feature will then enhance reliability except for the wrong information case. Therefore, the overall reliability is certainly increased.

If reliability nevertheless is not sufficient we can enhance information reliability. For example, if we have telecommunication equipment with an information channel and a guard channel, the guard channel(s) can be used to activate an alternative "basic" setting. This basic setting should be chosen to cope with our primary concern (dependability or security).

In the example of a 3-terminal line Figure 5.2 shows the possibilities for the protection at substation A:

a) no breaker-open or both breakers open received from substation B or substation C: setting Group 1
b) breaker-open received from substation B only: setting Group 2

c) breaker-open received from substation C only: setting Group 3
d) upon receiving guard channel alarm: setting Group 1 (or 4)

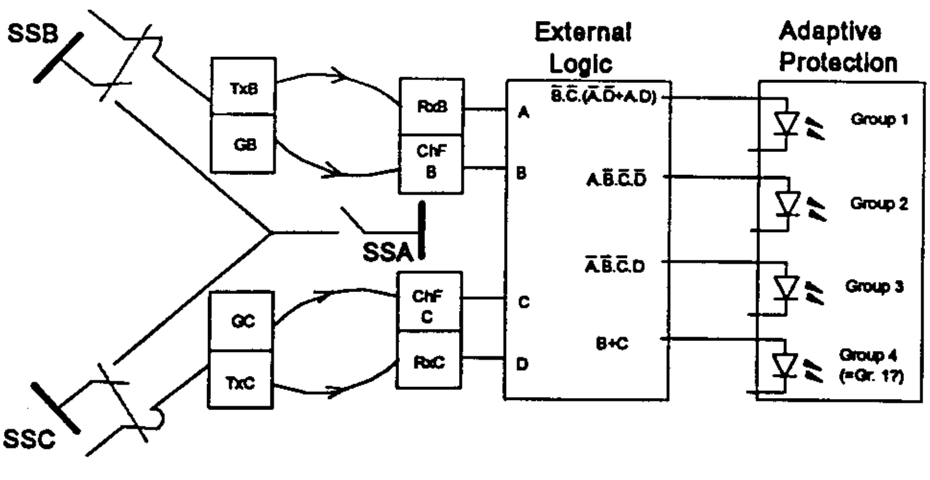

Figure 5.2: Adapting setting groups in a 3 terminal-line application.

If the communication link consists of RS232 or optical fiber, it is possible to create more "intelligent" messages, with which transmission reliability is inherently controlled. These types of communications may nevertheless have limited use for demands coming from passive elements such as circuit breakers, other protections, etc., due to:

a) bandwidth and speed needed in comparison to the simplicity of the message, especially for dynamic applications
b) the specific protocols to be created and to be cast in a form acceptable to the sending and receiving element (lack of standard)
c) less flexibility in user specific order combinations (except when it is foreseen inside the protection).

Moreover, in general, such devices use the remote MMC communication ports, which covers the complete dialog. This means that this communication type is slow and more dedicated for dispatch or protection applications of a non dynamic type.

Another aspect of "incorrect demand" of adaption can be added for centrally directed applications: intruders. To assure security the existence of "password" access is generally used, and indispensable.

5.2.1.2 Several demands at the same moment

If a protection system has different digital inputs for each of its settings it is possible that two setting adaptions are asked at the same time. Suppose for example the opening of 2 breakers on a 3-terminal line where each of them activates an alternate setting, the protection may react in a certain way:

a) it neglects both incoming signals
b) it takes one of the two activated settings
c) it takes another setting

In the example of Figure 5.2 the problem is handled by what is called the "external logic". Due to this logic all signal input combinations are properly handled and the relay cannot theoretically receive several demands at the same time. The price for that is considerable external logic represented in the figure by boolean formulas. But as all this happens outside the relay and is not foreseeable it does not relieve the manufacturer of the task to take into account the handling of several demands. This should be done by clear priority rules of which the user is made aware.

Priority rules or the processing of several demands at the same time can be handled by software or can be inherently determined by the hardware. For example:

a) each input activates an alternative setting and priority rules handle multiple demands, so N input relays can handle N+1 settings.

b) each input state combination unilaterally determines a setting, so N input relays can determine 2^N settings.

Figures 5.3 and 5.4 show both approaches for the example of the adaption of the settings of a 3-terminal line as a function of the circuit-breaker position:

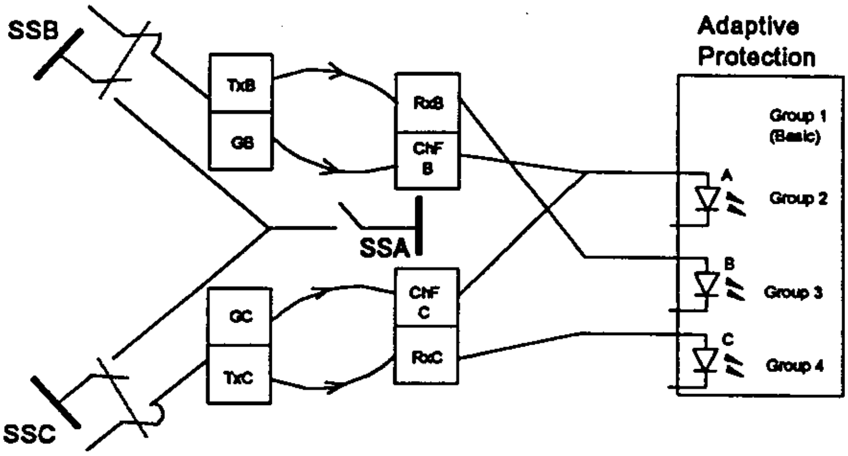

Figure 5.3: N input relay for N+1 settings. Lowest group number has priority over highest.

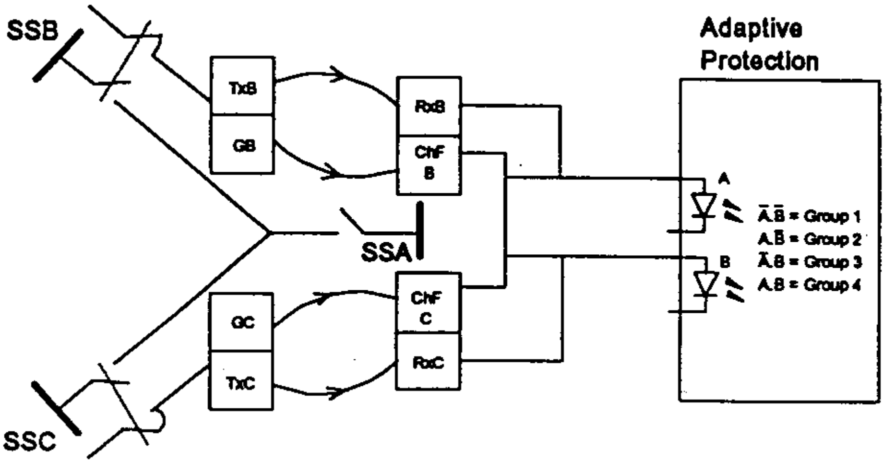

Figure 5.4: N input relays for 2^N settings.

Where the system is shown in Figure 5.4 uses less inputs, that in Figure 5.3 on the other hand is more flexible and creates "weighting factors" in the decision. Indeed, if the lowest setting group number has priority over the highest, 4 input combinations correspond to setting group 2 (most dependable), 2 to group 3, and 1 to groups 4 and 1 (most secure).

Group Selection for each input combination for the example of Figure 5.3	
Activated Inputs	***Selected setting group***
None	Group 1
A,AB,AC,ABC	Group 2
B,BC	Group 3
C	Group 4

For the system of Figure 5.4 each setting group has the same weighting factor in relation to the input combinations (not in relation to the original signals RxB, RxC, ChFB, ChFC).

What is the best solution? Considering again the application of Figure 5.3, we see that we have created a logic where the "loss of channel" gives the most dependable setting, the "breaker B open" the second most dependable and the normal network state and the "breaker C open" the most secure setting. Is this what we desire? If we give priority to trip the line rather than to avoid unwanted trippings we would like to give the highest setting values the highest weighting factor. For both single breaker open situations we have normally a lower setting so we want a more secure solution which corresponds to groups 3 and 4. But for all breakers closed (Group 1) we normally have the highest setting and there we don't have a dependable solution in the example. Several remedies are possible:

a) use a 4 input system instead of a 3 input system.
b) use the same settings for the channel fail and for all breakers closed condition.
c) make a more complex logic at the input so that Group 2 corresponds to the all breaker closed condition and Group 1 to the channel fail condition. This seems an interesting solution if we want the channel fail condition to increase the setting even more than the basic one. Some utilities do it (on single phase faults) when the teleprotection channel is lost.

As this example shows, which solution is the best is dependent on what the user wishes. Therefore, flexibility is necessary.

The most flexible solution is to use programmable logic (and, or, . . .) in the protection so that the user can determine his own combination logic. By programmable input logic (which exists in most of the digital relays) the user decides how many inputs the user wants to use for how many settings and how to combine them. But the user has to be aware that the risk of human mistake is also the greatest in this system! Even if the manufacturer has to foresee that no logic can be defined where contradictory or unforeseen states are created - this is a requirement - the user has the responsibility not to create incorrect assignments (see Section 5.2.1)!

Figure 5.5 shows the same example with a protection with programmable logic. The logic created in this application associates 1 well-defined combination of the 3 inputs with each of the alternate settings, the other 5 combination possibilities give rise to the basic setting. Consequently, the basic setting is very dependable, the other ones very secure. The security of the channel fail setting is also enhanced due to the necessity of no received input and by limiting the action. This works under the condition that received Rx and channel fail ChF are complimentary.

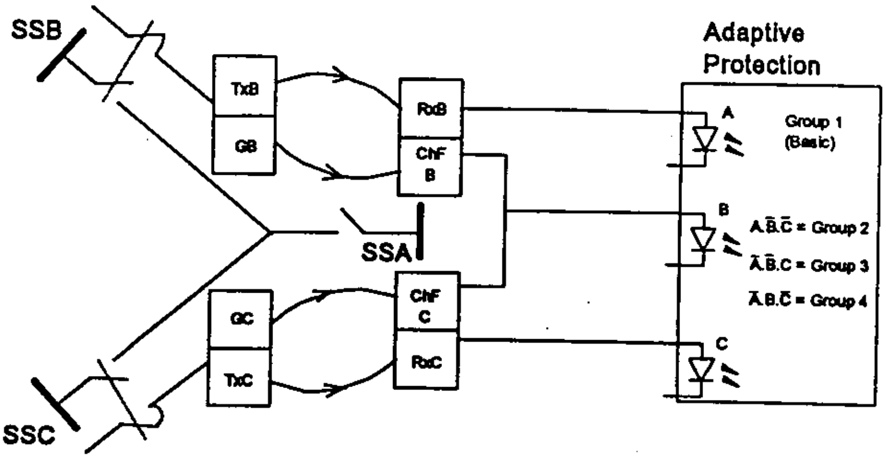

Figure 5.5: Adaptive protection with internal programmable logic.

5.2.1.3 Time domain boundaries on demands

One of the boundary conditions that can exist on adaption is the period in which the demand may take place. In some systems for setting group adaption, this adaption is only allowed under "quiet" conditions, in other systems dynamic changes are allowed.

To avoid activating this failure mode:

a) the manufacturer should limit the possibility to create such modes.
b) the manufacturer should clearly define the conditions in which adaption can take place.
c) the user has to ensure that the manufacturers conditions are respected.

Primarily, the manufacturer should take all the precautions to handle conditions linked with the capability of the equipment. Some examples:

a) access via optical channels should not be allowed if the equipment can not handle dynamic changes.
b) clearly define the priorities of the adaptive system. When a change of setting is called for during the start of the protection, will the old setting group be maintained and delay the switching, or will the protection be blocked until switching is achieved? What if a second change is requested before the first adaption is completed? Will the first adaption be stopped or completed? What is the time delay? (In the example of Figure 5.5, we can imagine for a fault on the line the tripping at busbar B followed by the tripping at busbar C some milliseconds later, or a quick setting group change from Group 1 to Group 2 to Group 1 again.)

These kinds of problems have to be solved in the design of the system.

The manufacturer should also inform the user about these limits so that the user may evaluate available options. A good description including all technical aspects in the user's manual is therefore indispensable.

Last but not least, the user should make the application conform to the specifications. This will probably be the most difficult part. Let us take again the 3-terminal line application.

If we use a static adaptable system (i.e. either the setting group switching takes too long, or the adaption is processed under low priority) it will not be useful, and may even be dangerous to use circuit-breaker information to switch the settings because the setting state will not correspond to the breaker state during a short time period, and the breaker position changes during a fault on the line. We may eventually decide to use only adaptive settings for long periods of open end condition as inferred from the position of the disconnects. The risk of dynamical changes exists even then (example: fault created by opening a disconnect while carrying load), but the risk can be taken if the adaptive system can recover from this condition. Referring to Figure 5.5, this risk can also come from the chattering of the channel guard signal (e.g. fading on a microwave system) which causes the settings to alternate between setting group 1, 2 or 3 and setting group 4. To avoid problems of this type it is necessary to add a switch-on delay set in accordance with the dynamic capabilities of the relay.

Even if the adaptive system is to be used for dynamic functioning, we should be aware that demands during dynamic network states (e.g. faults) can create reliability problems for certain applications due to the inevitable delay between change of network state and adaption in the relay. And in some dynamical situations we may not want the setting group adaption to work. For example during the single-phase opening of a breaker.

More difficult problems can also occur during dynamical states. Experience with classical applications having time domain boundaries have generally led to special timer logic to overcome such problems. For example, permissive overreach schemes can not work reliably during current reversals without special facilities. Due to the general definition of the function ('adaptive setting') it can cover numerous applications, where only users' imagination is the limiting factor. It is therefore very difficult for the manufacturer to foresee "specific" timer logics for all of them. The best solution is to add timers in the programmable logic at the input of the relays. Our example would then appear as shown in Figure 5.6:

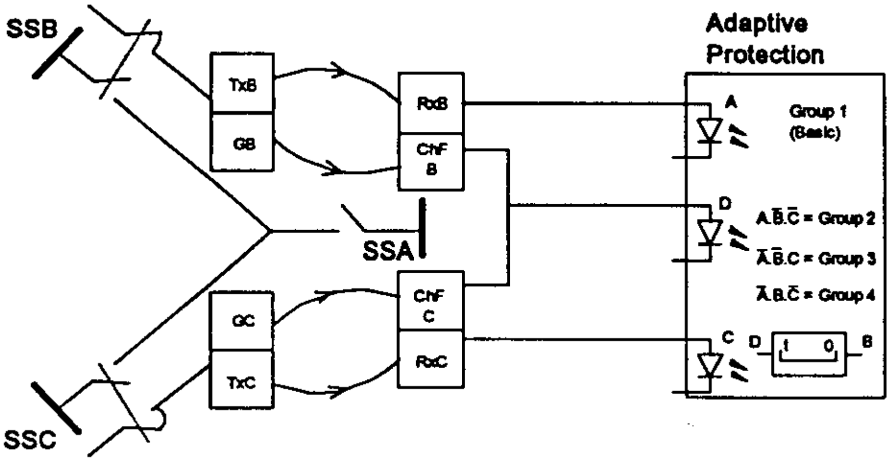

Figure 5.6: Handling time domain problems with timers in the programmable logic.

5.2.1.4 The data corresponding to an adaptive state are wrong

In case of a protection with several setting groups the risk of human error in introducing the settings is increased due to the high number of parameters. This risk will always exist and defects can only be detected indirectly by injection tests. But injection tests should then be performed on each used setting and be based on an independent setting library.

This, of course, increases the work during maintenance tests and it is advisable that special features are added to limit this increase (example: the protection shows on demand the fault location in % of the setting group so that the tests should not necessarily be repeated.)

The best way to limit the risk of bad settings is a good man-machine interface: engineering studies and preparation at the office, good overview of settings, copying and comparing possibilities (when minor changes are performed), clear print-outs, calculation programs to verify setting, etc.

A special case of wrong data in a setting group is the one where a switching occurs to a non-used group. Suppose we use only two out of five alternative settings groups, how can we limit the risk for that? This depends on what features are foreseen in the protection:

a) when binary inputs are programmable we should avoid assigning an unused setting group to a binary input state.
b) if there exists a hardware or a software technique to block the use of that setting group we should use it.
c) if nothing special is foreseen it may be wise to fill the non-used setting group with the data of the most used group (basic group).

5.2.1.5 Processing traps

Processing traps must be seen as "bugs". No processing state can be left uncontrolled. Although this seems self-evident, it is well known that the probability of programming bugs increase with the complexity of the software. Knowing that each adaptable feature adds some weight to the complexity, special attention to this aspect is called for.

The problem of complexity of a protective system goes far beyond the specific application of adaptive features - other sometimes less interesting features can also be taken up in this connection - and will therefore not be handled here.

The weight of complexity in "processing traps" can however be limited by clean manufacturers' development. Some rules of common sense (Quality Assurance standards):

a) good documentation (logic schemes) prepared before software is developed.
b) good organization of tasks in well defined software modules ("routines").
c) writing software in a high level language.

Some examples for the setting group adaption where care should be taken:

a) several settings activated at the same time (see Section 5.2.1.2).
b) a higher priority task (fault) occurs during setting transfer.
c) the setting group is undetermined or is not allowed (if blocking exists).

5.2.1.6 Failures that disturb processing

One of the important advantages of digital protections is the existence of self-check functions. A supervisory program checks supply voltages, processors, RAM and EEPROM memories, program code, etc. by reading-writing, check-sums, comparisons and so on. If an error is detected an alarm is raised.

Adaptive features should allow no exception to this rule, and should be checked in the same way.

For example, for the setting group problem we can imagine input logic supervision, routine-checks, data validity controls, saving data groups on different EEPROMS, etc. An exception can be made to the handling of some of the failures: it is not always necessary to block the whole relay. For example, if during data comparison (double save set or checksum) an adaptive data group is found corrupted or the input logic fails, it may be desirable to continue working with the "basic" setting group. An alarm should be raised but the protection function stays available. If the basic setting group itself fails, another group could be activated. If we have a priority system from the lowest group setting against higher setting groups, the system could be made to select the group above if the checksum fails. This of course will not cover all user specific requirements, so we could again think of programmable logic inside the relay. The setting group selection logic should be able to combine inside information from the relay in its logic. This could lead to the situation shown in Figure 5.7.

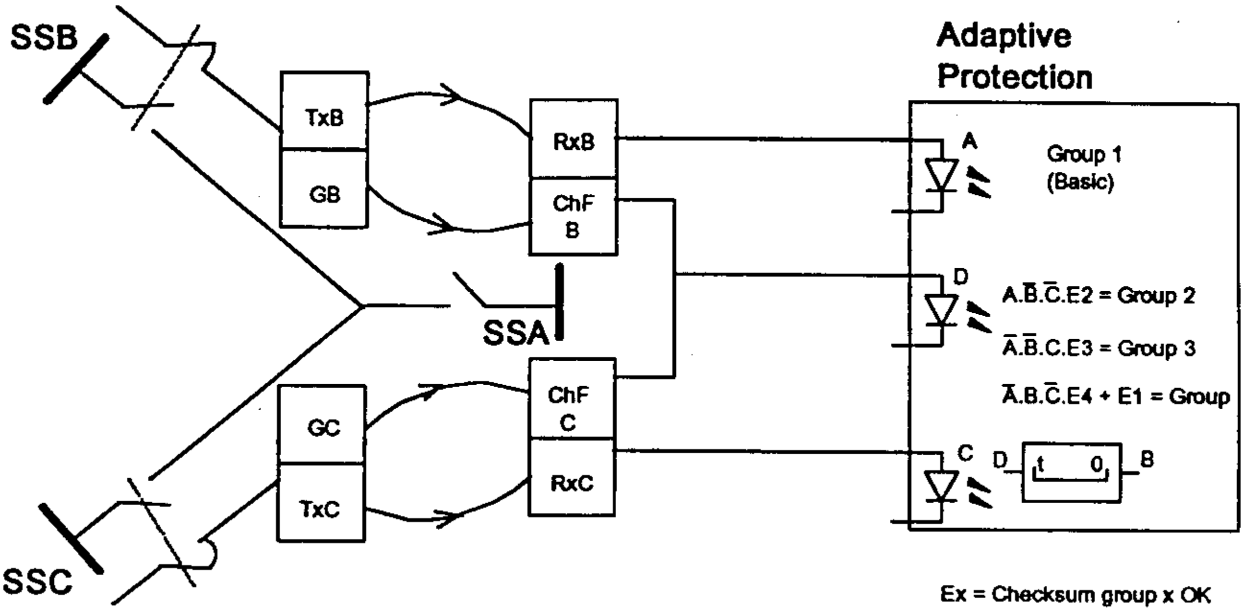

Figure 5.7: Setting group adaption conditioned by inside information.

Note that the possibility to adapt the setting as a function of internal information is not only interesting to respond to failure modes, but has also application benefits. A series of applications mentioned in the questionnaire could be solved by this possibility. We could then, for example, switch settings as functions of fault type (multiphase vs. single phase).

5.2.4 Conclusions for the case study

The study of the problem of failure modes and recovery systems for the example of changing the setting group as a function of a logic input has revealed a number of conditions that have to be fulfilled to guarantee optimum performance. It may be surprising that at first sight uncomplicated adaption has led to this complexity. The main reason therefore is the generality of this adaptive function. There are numerous application possibilities for this feature. The manufacturer should therefore make abstraction of the application itself and create an environment that is independently fail proof. The manufacturer also has to make clear to the users what are the limits of the system. For each imaginable failure mode the recovery mechanism should be described. And finally, the user should verify that the application fits into these specifications.

If we summarize the solutions we discussed to handle the different failure modes we have:

a) information reliability can be achieved in classic ways ("and" condition to increase security, "or" to increase dependability.)

b) the protection should be able to handle all combinations of input conditions. Some flexibility is necessary to solve all user's demands. There must be a basic or "fall-back" mode.

c) dynamic situations should not create an internal failure mode. They will however, always create a temporary "inadaption" of the system. The user should be aware of this (be informed about the application limits) and take precautions where necessary. Availability of internal timers would be interesting.

d) MMC should be developed to limit human error. Tools should be at the users disposal to detect errors easily.

e) An adaptive (setting) equipment is only justified if extensive self-supervision is present. This implies application in digital relays.

The ideal protection would therefore be a digital one with extensive supervision, clear handling rules, well documented, easy MMC and programmable logic at the users disposal to determine setting group selection. This logic could include boolean operators, timers, and combination possibilities with internal information.

5.3 Other adaptive systems

Studying a case of one special application has the advantage that it provides an illustration, but on the other hand it hides some important failure modes of other adaptive systems. Although it is not the purpose of this work to make a summary of all possible failure modes, it would be interesting to briefly look at another type of adaptive system, the one based on analog inputs.

The different specific parts we had in the previous case study are still valid here:

a) demand for adaption
b) existence of boundary conditions
c) existence of data for adaptive states
d) the processing of the demand.

The demand itself has now become a permanent demand. It is not defined by states but by a permanent analog input. An example of this would be the introduction of the earth current of the parallel line to compensate mutual coupling. It is clear that if the demand disappears we would like the system to work as if we had no mutual compensation. This is normally inherently so. On the other hand we would like the adaption to work as it should and have to be careful with polarity. These conditions can be difficult to detect.

The biggest problem however is related to the boundary condition of synchronism. If it is not possible to time-align the external signal with the internal ones big errors can be created. Several degrees of synchronism needs can exist:

a) rectified analog signals will be less demanding. They are normally used for slow changes (steady state conditions). There is a temporary risk of inadaption if an action is asked at the time of change of signal.

b) sine wave analog signals should normally maintain the synchronism of the phasors (order of a fraction of a degree). There is a permanent risk of inadaption if this condition is not fulfilled.

The example of mutual compensation is of the last type. The synchronism problem will however be limited because it is a local application.

For remote signals more complex features are necessary to maintain synchronism. Examples:

a) create a message loop to measure time (see line differential protections). This works if there is a 2-way communication with equal transmission time.

b) using a common external time signal (such as a GPS satellite pulse) and send a time tag together with the signal.

Communication always creates a time delay, so at the receiving end there should be a time alignment.

By these features we can try to get synchronism but how can we detect the loss of it? The signal itself cannot inform the protection about it, unless we compare it with other signals with which we can recalculate the phase or unless GPS time-tagging is used. We have the time information itself on which we could make some verifications (detect excessive changes, defining minimum and maximum limits, etc.) and we could eventually use an alarm, if it exists, and we can introduce it in the protection.

5.4 Conclusions

Through the study of failure modes and recovery systems of one specific case it has become clear that the gain in reliability by using adaptive protections is related to the application and to a thoughtful development of the system. Undoubtedly adaptive features add some weight to the complexity of the protection. Specific failure modes will be created and consequently recovery modes must be designed. The increase in complexity may be accompanied by a decrease of reliability in the system and should therefore be balanced against the gain in reliability of the application itself. If we can find a reliable protective solution without adaptive features it is certainly the best solution. But as protection engineers are more and more challenged to find solutions to previously unprotectable network situations, adaptive protections become a necessity. If we use an adaptive feature the risk of unrecoverable situations should be limited.

We have tried to give a framework in this chapter to study the failure modes knowing that it is impossible to enumerate them all. A basic requirement for the successful use of adaptive features is a sound concept within the protection itself. The manufacturer has to consider in the development all possible adaptive states, even if they are not real, and control the response. Limits will undoubtedly exist, for example in the response time. This is acceptable as long as the user is informed about it. The manufacturer should also counter the increased complexity by good communication, verification and supervision systems. And finally the possibility must exist inside the protection to use the adaptive features in an optimum way.

An important requirement is that the adaptive feature be used as it should be. This is the user's responsibility but the user must be informed about all the requirements. Under all these conditions it can be concluded that, in spite of the specific failure modes created by the adaptive features, the overall reliability due to the adaptive features could be greater.

6. PROSPECTS FOR IMPLEMENTING ADAPTIVE PROTECTION SYSTEMS

6.1 Potential advantages

Adaptive protection offers significant possibilities for improving the current behavior of control and protective systems. New features may be included in digital relays (such as load flow compensation in distance relays or adaptive reclosing) that would improve the individual performance of these devices. In addition, increased and more readily available information about network conditions would allow settings to be automatically adjusted to conform to existing configuration of the network. It is also conceivable that a central computer, knowing at every moment the topology of the network, could calculate and transmit the most suitable settings to protective devices.

Two main sources of problems may delay the use of adaptive protection:

a) The need for new communication channels with more stringent requirements due to the greater amount of information to exchange, higher speed, and protection against noise. In some cases, the cost of these new channels could make certain applications of adaptive protection unattractive.

b) The need to change the organization of power utilities, manufacturers and industry committees such as IEEE or CIGRÉ. Some changes may be necessary because the traditional boundaries between control and protection devices, engineering and operating and standards making of the various disciplines are broken by this new technology.

6.2 Utility view

Implementation to adaptive relaying techniques requires two basic conditions:

a) Use of digital relays. This is also an economic issue, and is quite crucial if there are a large number of old substations.

b) Availability of communication facilities with enough capacity to serve the needs of adaptive protection with required speed. This aspect is often not a problem in many utilities, because communications have been developed to serve a number of other applications, such as monitoring, supervision and control.

Because adaptive relaying can sometimes incur significant costs and encroach upon a sensitive aspect of power system engineering, i.e. protection, which operates in a traditionally conservative environment, a step-by-step implementation is essential.

It is possible, for instance, to propose the following steps:

a) Possibility of remotely changing the relay settings, non-automatically, by the engineer usually responsible for protection settings.

b) Automatic adjustment of relay settings (chosen in a predefined set, or a result of dedicated computational tasks) depending on network status, which may be locally or remotely monitored.

c) Integration of protection devices and control functions (e.g. out-of-step relays) with Energy Management System (EMS) functions.

The first step is not a real "adaptive relaying" application in the present sense, but is perhaps the most important one because it brings out the advantages of the new technique without the risks resulting from the automatic setting changes.

An aspect that must be stressed in adaptive relaying application is the vital requirement that the protection and operation people know at each moment the actual relay settings. Because of this requirement, a communication link between relays and control centers is essential.

Before the adaptive relaying concept can be implemented in an operating utility, there are several factors that must be accommodated. Basic to any implementation process is an understanding and acceptance of the advantages and an appreciation of the risks involved. Understandably, relay engineers are historically conservative in introducing radically new protective features. They are responsible for the security and the integrity of the power system and, over the years, have attained a very high level of successful performance. The effect of any new concepts or equipment must be measured against this record of achievement.

Having said that, however, it must be noted that protection concepts, equipment, schemes and circuits have evolved and significantly improved with technology. Recent surveys, technical papers and seminars give a clear indication that relay engineers recognize the advantages of utilizing digital devices and have introduced adaptive features in both protection and control. Relay engineering, perhaps more than any other discipline, must take into account the compromises and limitations to which relays are subjected to cover all of the system configurations and operating conditions. As a result, in light of the growing acceptance of computer relays, extensive studies have been conducted to implement adaptive relaying without adversely affecting existing system protection.

Adaptive relaying can be described from a variety of viewpoints, depending upon the specific application involved. It is instructive to consider a hierarchy of implementation levels with increasing input-output requirements.

The least complex layer involves communication within the station. Local inputs, e.g. current, voltage and switch positions to describe the state and configuration of the station, are known from equipment within the station. Similarly, the outputs involve local action such as changing breaker trip sequences, rearranging current inputs or changing relay or reclosing timer settings. Familiar examples of adaptive protection at this level are the changes associated with the application of a bus tie breaker for breaker maintenance in which a standby complement of relays is installed with the appropriate settings for the line associated with the breaker being maintained, the transfer of a backup potential source or the implementation of overall bus differentials during station switching. Local level adaptive relaying does not inherently require digital devices. Many of the concepts can be accomplished with hard-wired contacts and auxiliary relays although the complexity and impact on reliability using discrete devices and interconnection wiring is much greater.

The next level is adaptive relaying between relays at adjacent stations. A typical example would involve a three-terminal line where the presence, absence or level of the contribution from one of the terminals would be recognized and the settings of the remaining distance relays adapted to this configuration. At this level, communication starts to play a more important role. The simplest use of communication channel would be an on-off signal indicating whether a remote circuit breaker is open or closed. The assumption is that the level of the contribution is fixed and the adaptive action would be taken during steady-state operation. A more complex scheme would involve an analog signal that transmits the actual in-feed contribution. This, of course, would have to be done in real-time with high-speed communication channel.

The highest level of this hierarchy would be adaptive action taken from a central location such as a Control Center to a station. The central location would be the data gathering point for the system or a strategic part of the system. Important data such as the real time evaluation of the system configuration, Thévénin equivalent voltages, planned outages or generation changes would be known or calculated. This information could be transmitted to any or all stations to adapt relay and control parameters to this new or pending situation. Again, the communication channel becomes an important element in this concept. Not only must the bandwidth and speed be appropriate, but there must be feedback to recalculate the total system, relay and control picture.

It has been noted that as the adaptive implementation moves from within the station to between stations and finally from a central location to many stations, the role and burden of the communication channel assumes greater importance. Although communication channels have always been vital elements of primary system protection, the interface between the relay and the communication equipment has been clearly defined. It usually was determined by the equipment itself. As a result, even the separate responsibilities between the relay and communication engineer were similarly defined. An effective relationship has developed in which the requirements of each discipline is made known and accommodated with very successful results. However, as the protection and control concepts have changed with resulting equipment design changes, the interface between communication, protection and control has become less distinct. This, in turn, has blurred the specific responsibilities of each discipline.

It must therefore be recognized that adaptive relaying will not only have an effect on protection and control. It will also significantly impact the organizational responsibilities of an operating utility. The engineering services associated with relay planning and settings will be more intimately involved with station design, control and relcosing practices and the overall system operation, activities which in the past were related but with responsibilities clearly defined.

6.3 Manufacturers' view

The growing acceptance of adaptive relaying will similarly affect the suppliers of digital protection and control equipment. The entire adaptive concept requires a degree of integration of functions that does not exist with discrete electromechanical or solid-state devices. This will impose a level of expertise, or at least a sharing of technology, that may not be present in a single manufacturing location.

In addition, adaptive relaying introduces operating parameters into the protection and control function and will, therefore, require the equipment supplier to interact very closely with the user. The result may be customized equipment which would adversely affect manufacturing efficiencies or an overall design that encompasses all options which would affect the cost. The interaction with the user will also have to be modified. The usual practice of a sales engineer representing a single product and establishing and maintaining contact with a parallel user group will not be adequate with the integration and interaction of functions.

The manufacturer faces the same organizational changes as the operating utility. The various disciplines that now interact with each other but are still independent entities will have to establish a new method of operating or combine into some common organization and manufacturing unit.

6.4 Industry view

The acceptance of this concept, and the means of implementing it must similarly be accepted by all those who are involved. The expertise of specialists will be expanded so that much more of each discipline must be known to a greater extent by everyone than has previously been required.

This interaction between the different technologies and organizations also extends to the development of standards. In the past, interaction between the various disciplines has depended upon liaison representatives, primarily to assure that a proposed standard does not encroach upon, or misrepresent, another technology. With the integration associated with the adaptive concepts, this method of interaction will no longer be sufficient. To take this one step further, the industry organizations themselves must be organized or operate in such a fashion as to insure this integration and cooperation.

6.5 Communication concerns

It has been indicated in several sections of this report that communications and control are an integral component of this concept. Communication engineers and relay engineers have always had a symbiotic relationship and all primary relay schemes depend upon the reliability and availability of a communication link. The adaptive relaying concept introduces another dimension to this relationship. Traditional interfaces and the concomitant responsibilities will be altered. Control strategies, normally the province of system operators and dispatchers, may be implemented by the protective equipment. Again, acceptance, responsibility and detailed implementation will be shared.

6.6 Conclusions

As with most new technologies, the implementation of adaptive relaying will be gradual; probably as additions to existing equipment and schemes. Electromechanical and solid-state relays do not lend themselves readily to this concept without the addition of complex circuits. Such additions degrade reliability and seriously affect maintenance and testing. In selected areas, however, where the advantages are great enough, such additions may be warranted. It may be possible, and preferable, to add digital devices to supplement the existing relays to provide the adaptive features such a improved logic, self-checking or setting changes. This may be possible without degrading the protection since digital devices can monitor themselves and remove themselves from service, leaving the situation as it was originally. As digital devices begin to replace the existing electromechanical or solid-state relays or accommodate system changes, the gradual implementation of adaptive relaying will be more easily implemented. The progression will be from individual digital relays using the improved features but without the need for extensive data, to devices operating on local data supplied by equipment existing in the station and finally to the more complex adaptive functions including the exchange of data between different stations and between stations and control centers.

7. MESHING OF PROTECTION AND CONTROL, AND CORRESPONDING RESPONSIBILITY

7.0 Introduction

Both the protection and control functions are often present in the same devices and systems. Also, many functions traditionally categorized as protection functions are in reality performing control. In this connection, out-of-step relaying, under-frequency load shedding and automatic load restoration tasks could be considered to a large extent to be control tasks. As the concept of adaptive relaying evolves, it is likely that the distinction between such protections and control will become less precise. This is not surprising, as one of the important aspects of adaptive relaying is the feedback signal, which brings to the relay information about the state of the power system. And of course, feedback is also an essential element of most control systems. It thus follows that with the advent of adaptive relaying, it may be necessary to examine the relationship between control systems and protection systems, and consider aspects of this interaction. The aim of this section is to examine how adaptive relaying strategies impact on common protection and control fields.

7.1 Protection and Control: Differences and Similarities

It is useful to give the following operational definitions of protection and control functions:

Protection function:

To eliminate faults or unacceptable operating conditions for a component, and related effects on the network.

Control function:

To act on the network (by means of appropriate "control actions") in order to maintain the current normal secure state or to eliminate insecure, emergency or restorative states driving the system to normal secure state.

Interactions between protection and control functions are determined by the devices needed to perform these functions.

7.1.1 Protection devices

To better understand the interaction between protection and control, it is useful to define the following taxonomy of protection devices:

(a) Protection devices completely devoted to protection functions (e.g. differential protection);

(b) Protection devices devoted to protection functions but with sections available for control functions (e.g. distance protections with out-of-step relays);

(c) Devices mainly devoted to control functions but usually considered as protection functions (e.g. load shedding equipment)

It is commonly understood that protection and control fields refer to devices of type (b) but also, for historical reasons, to devices in category (c): to perform control function (e.g. emergency control actions) it is necessary to use protection devices. Adaptive relaying strategies enlarge this common field, through communication links between control center computers and protection devices.

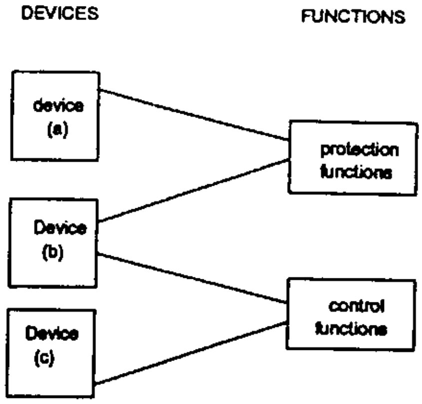

Figure 7.1: Protection devices and protection/control functions.

7.2 Need for communication

The basic idea of adaptive relaying is to adapt the protection automatically to changing system conditions. It can be shown very clearly that even in the case of a simple two-machine system a stand-alone relay has no knowledge of the remote infeed into the fault. In practice we are confronted with meshed networks. A stand-alone relay has no chance to adapt itself properly to changing system conditions, without information from outside. For example, the magnitude of the load current at relay location does not give clear information about system conditions. A high load current can be the result of either high loading conditions, or of open parallel lines.

Clearly, communication between related devices or functions is an indispensable part of the adaptive functionality of protection. The operational data have to be exchanged.

Communication systems may be established completely separately for both protection and control. However, common use of one communication system for both protection and control reduces the cost. If an effort is made to set up a redundant communication system, it seems better if both functions can use common communication links to get the benefit of redundancy for both, protection and control, instead of having dedicated channels for each.

7.3 Main Requirements

The basic philosophy behind the adaptability must be that the adaptive function has to improve the behavior of protection and shall never make it worse. Availability and reliability of the main protection shall never be in question if the adaptive relaying function fails, for whatever reason. In applications where the adaptive function is a fundamental part of main protection, e.g. in the case of selective protection of multi-busbar systems, the availability and reliability requirements on communication are the same as on the protection.

7.4 Function Flow

The basic functional flow of any adaptive relaying function will consist of the following steps:

1. Determination of changed power system conditions
2. Decision for adaption
3. Adjustment of protection

4. Report to the personnel responsible

Where each of these steps shall be performed and what the time frame to do it will be will vary among different adaptive protection functions. Apart from some rather simple applications, the decision for adaption will take place outside the bay protection units, i.e. at station or network control levels. The time frame will be on line when regarded from the network control but will be off-line from the point of view of relay operation.

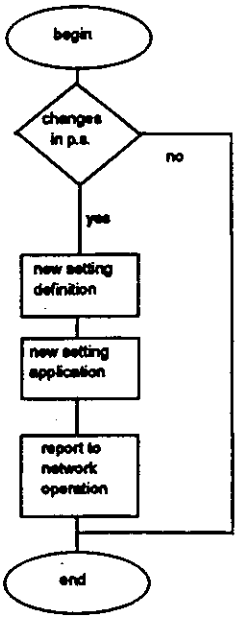

Figure 7.2: Function flow for adaptive relay implementation.

7.5 Interaction Protection-Control

As mentioned above the interaction between control and protection has to be of an operational nature. To establish this, both appropriate technical and organizational solutions are necessary. Computer technology definitely offers the possibility of common use of hardware, of data and of communication channels. The problems that arise are concerned more with the organization and responsibility, rather than with technical feasibility of the concept.

7.6 Assessment of Responsibility

The electric utility companies must decide the future organization and allocation of responsibility, influenced by new technology with common use of hardware, of data and of communication channels.

From the utility point of view, in the area of protection and control systems operation, the following fields of activity can be identified:

a) design and specification
b) installation
c) maintenance
d) testing
e) setting and coordination

f) performance analysis.

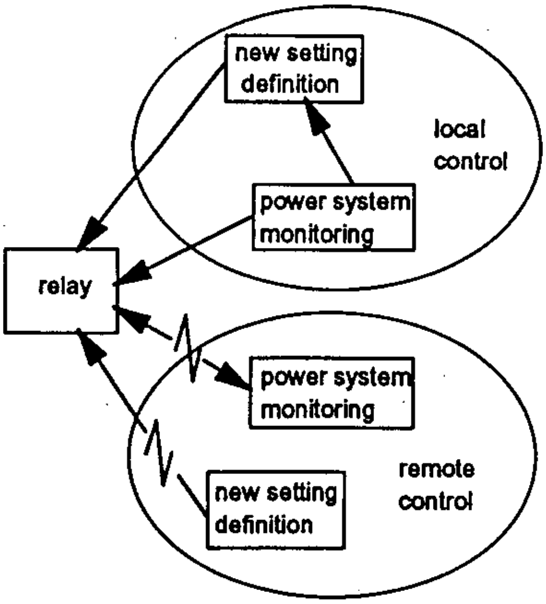

Figure 7.3: Physical scheme for local and remote adaptive relaying application.

Usually, the responsibility of activities (b)-(d) is typical of power plant and station operation, while for the activities (e) and (f) the network control authority is responsible. The network control authority can be concentrated in one control center, or broken up in a hierarchy of main and regional control centers. Activity (a) is performed both by network control and power plant and station operation units.

The main interactions and data exchanges between protection and network control in applying adaptive technologies involve some EMS on-line control functions.

In *on-line monitoring* by means of telemeasurements and telesignals, network changes and eventual emergency conditions are detected. To perform this function it is useful to have information about protection operation, e.g. to detect faulted elements. If relevant changes in network structure occur, new settings are sent to protections, or suitable telecommands to switch them to another predefined setting set.

In *emergency control* it is useful to know the protections status and some data as measured by protections (e.g. impedance) to define some control actions. Such actions can consist in sending block or trip commands to some protections experiencing power swings, or to send a new setting to starting relays of distance line protections, to avoid overload trips.

In *restoration control*, especially after a black-out, it is again useful to know the protections status. In this phase, the strong perturbations in operation magnitudes (voltages, frequency, etc.) can require temporary new settings to some relays (e.g. underfrequency, over/under voltage, etc.) to avoid further trips during system re-energization.

In the following table, the data exchanges between EMS function and protections are simply represented.

	Protection data	EMS function
send to EMS	status (start, trip, etc.)	on-line monitoring
receive from EMS	new settings	
send to EMS	status and measures	emergency control
receive from EMS	block or trip signals	
send to EMS	status (start, trip, etc.)	restoration control
receive from EMS	temporary new settings	

8. TESTING OF ADAPTIVE PROTECTION SYSTEMS

8.1 Introduction

Comprehensive testing of protection equipment has always been a complex process which should not be underrated and requires a deep knowledge of the electrical system plus the protection unit under test. For many years traditional protections have incorporated elements of adaptability (eg distance blocking schemes; voltage controlled IDMTL, etc) which have been effectively and comprehensively tested. The advent of digital or numeric protections progressively brought with it the introduction of communications input-output ports which gave the valuable mechanism of transferring and accepting large amounts of information. For this section of testing it is assumed that conventional protections do not use information from these communication input-output ports as part of their protection algorithm and that adaptive protections do use information from these communication input-output ports as part of their protection algorithm. For adaptive protections, therefore, these communication input/output ports have a significant effect on protection operation (see Figure 8.1 for possible protection configuration).

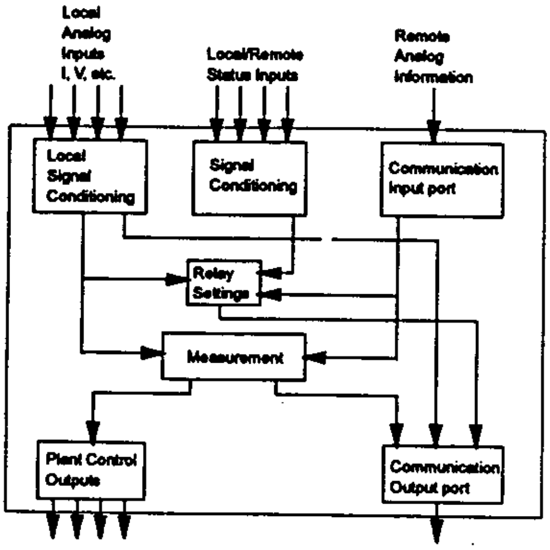

Figure 8.1: Possible adaptive protection functions.

8.2 Test classification and definitions

CIGRÉ document "Evaluation of characteristic and performance of power system relays and protection system" (SC34 WG 04 1986) classifies testing procedures into two basic categories which are further subdivided and illustrated in Figure 8.2.

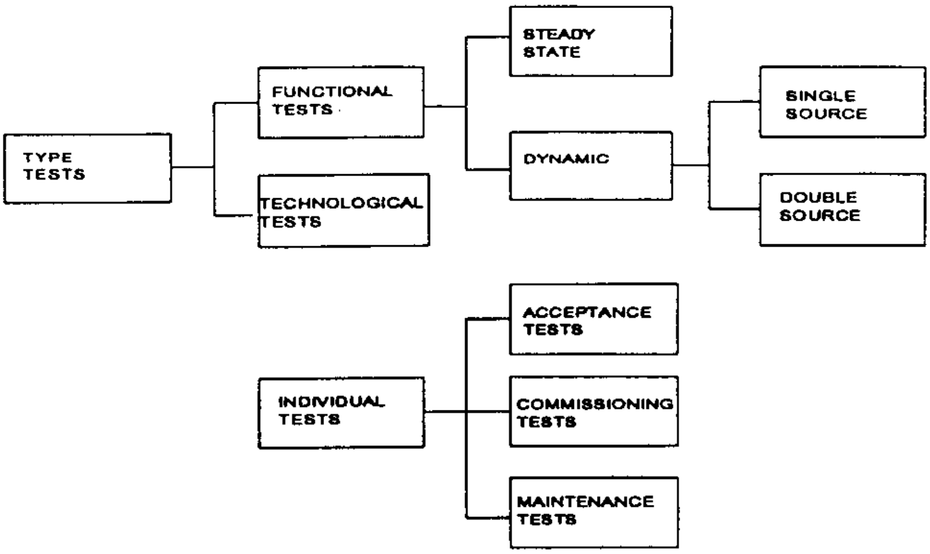

Figure 8.2: Categories of testing procedures.

Each test classification will now be considered in relation to adaptive protections.

8.3 Evaluation of Testing Adaptive Protection

The concept of adaptive protections involves one or more additional communication input-output ports but does not involve any radically new technology. It therefore follows that testing practices employed for evaluating conventional protections will be equally applicable to adaptive protections but that the number of tests required could significantly increase with the number additional settings or functions involved.

8.3.1 Type Tests

These tests aim to prove the given equipment or system has been effectively designed to meet all appropriate national and international standards requirements plus any manufacturers or application claims. To accomplish this aim these tests must be extensive therefore are generally done once on new products or products which have undergone significant change from the original design.

8.3.1.1 Functional Tests

These tests confirm the intrinsic accuracy performance and functionality of the protection under both steady state and dynamically changing conditions.

Steady State Tests imply that the input quantities (generally AC) are stabilized or varying slowly which generally means they are easily defined and the input quantities readily generated from various test circuits or equipments including Automatic Test Equipment (ATE). Testing of adaptive protections under steady state conditions should not cause any increased difficulty or concern other than the probable increased test volume due to additional input circuits.

Dynamic tests imply rapidly changing system quantities which means they are significantly more complicated involving many variables and requiring sophisticated test circuits particularly when double source circuits are involved. The following is a small list of some of the factors which need to be taken into consideration and illustrate the problems of generating appropriate input quantities.

- Saturation of CT's
- Spurious CVT transients
- Point on Wave switching and DC transient
- etc. the list could be very extensive

Dynamic testing of adaptive protections needs to consider additional significant factors such as:

- Response time between change of mode or setting
- Co-ordination with other adaptive protections
- etc. the list could be extensive.

There may well be significant differences for various generic protection types (distance current differential etc) therefore each must be considered on an individual basis with relation to additional functionality, settings etc.

Since the concept of adaptive protections could potentially involve a significant increase in protection settings, characteristics or alternative modes of operation then this will involve a correspondingly significant increase in testing at the development and Type Test stage. As these tests are normally performed once on a given protection the increased testing is probably acceptable.

8.3.1.3 Technological tests

Technological tests aim to confirm that the intrinsic design technology is capable of withstanding the environmental conditions and will continue to function safely within performance claims. These tests involve aspects such as electrical insulation, thermal withstand, EMC, climatic and mechanical durability. Since there is no radical new technology involved for adaptive protections then existing test procedures or standards should be equally acceptable.

The area of greatest concern will probably be to ensure the protection does not inadvertently change setting or mode due to external influences on the communication input-output ports such as Electro-Magnetic Compatibility (EMC), white noise, music pick up etc. This will result in an increase in tests to be performed but since they are normally performed once only during Type Testing then it is probably acceptable.

8.3.2 Individual Testing

These tests aim to ensure conformity of the protection to the original design or its continued operation.

Acceptance tests are generally performed on all dispatched products to ensure there are no manufacturing errors or shortcomings and that the product conforms to the original design. These tests can be quite extensive and vary greatly with different manufacturers in order that they can be accomplished in an economic manner. The growing use of comprehensive self diagnostic software plus appropriate test interfaces for ATE has curtailed the potentially escalating cost of testing increasingly complex protections. These techniques should enable acceptance tests to be performed on adaptive protection at similar costs to conventional protections. A typical format for these tests could be:

- Quality and Customer order checks
- Pre sets and calibration
- Characteristics and tolerances
- Dynamic range testing
- Operational checks

Commissioning tests aim to ensure that the product has travelled safely to site, has been connected correctly to associated plant and that the appropriate protection settings and operation have been validated. Since adaptive protections will have extra settings/functions then these must also be checked. The time and cost of checking these extra settings/functions is unlikely to be significant in comparison to the overall commissioning cost therefore is likely to be acceptable.

Maintenance testing aims to ensure that the product continues to function correctly and operate within limits. The tests are normally performed on an infrequent basis and aim to be non-invasive of the protection and system wiring. The use of self diagnostic software and ATE test interfaces within the protection should enable adaptive protections to be tested as economically as conventional protections.

8.3.3 Computer Simulation System

In addition to the above test classification there is a growing trend for manufacturers to computer model their proposed new numeric protections at the design stage so that its response can be simulated for various input conditions. If a propriety power system computer simulation package (EMTP etc) is linked to the protection model then the protection response can be effectively computer simulated for any power system disturbance.

Some numeric protections also incorporate data capture whereby the system current/voltage wave forms can be stored within the protection then downloaded to a computer for storage. It must be borne in mind that in these cases the data stored and downloaded from the protection is the Analog to Digital Converted (ADC) values and not normally a fidelity signal of the system condition since DC component removal and AC filtering frequently takes place prior to the ADC values see Figure.8.3 for possible configuration.

Protection ADC stored values are nevertheless very valuable since they enable the manufacture to replay the system condition and the protection response by using this data and by-passing the protection input conditioning on their computer protection model. This computer modeling has significant effect on design/development testing and system evaluation.

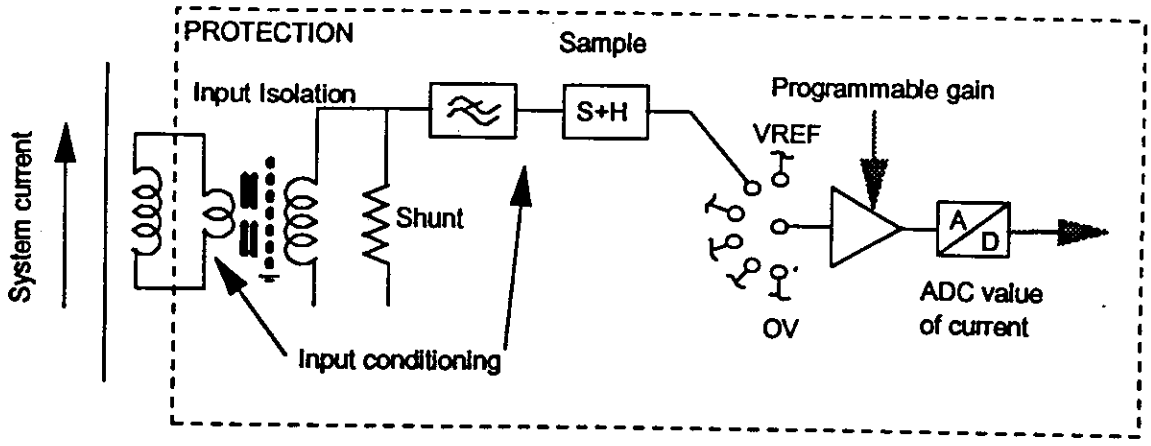

Fig 8.3: Possible configurations of test systems.

9. TRAINING AND ORGANIZATION

9.1 Introduction

A lot has been said and written about training for digital protections during last several years. In CIGRÉ the subject was handled at the Bournemouth Symposium in 1989, in the section 2B "Technical and organizational impact of digital systems" [11] and at the CIGRÉ-34 colloquium in Antwerp 1993, "Training and adaptation of engineers for digital technologies for protection and control of electric power systems" [12]. Both meetings did not explicitly touch the field of adaptive protection, but most of the training for specific elements on digital systems are closely related to those that make training on adaptive relaying different from training on older technologies. Therefore it is useful to analyze some aspects touched in the reports of those conferences. Generally speaking, the following points were highlighted:

- there is an educational problem (less interest in power system engineering)
- due to integration of different functions there is a necessity of a higher knowledge base and a different organization.
- there are restructuring problems (less people for the same job)
- the right training should be given to the right person
- there is a temporary problem due to the presence of different technologies at the same time.

Some of those points will be analyzed hereafter in relation to adaptive protection.

9.2 Interest in power system engineering

It is well-known in many countries that the interest in power system engineering is decreasing. Power system engineering is considered to be old fashioned with a lack of challenge towards new technologies. Students have the tendency to choose the most fascinating, highly challenging, and easily accessible techniques. Computer science is one of them: due to the enormous explosion of the PC-market, a computer is within everyone's reach at an acceptable price. And, with a computer you can do incredibly creative things.

Considering this evolution, the step towards digital technology for protection and adaptive protection techniques is a must. It puts a new challenge into the more traditional use of protection technology. It should be clear to young engineers that digital technique have also found their way into the well established field of power system engineering.

The challenge for the universities and high schools specializing in power system engineering is therefore to put their program into a new perspective. As it has been underlined by different speakers in Antwerp [12] the basic program should still be power system engineering but the techniques to present that program should be adapted to the environment that exists today. It appears that universities that have understood this strategy are the most successful.

Adaptive protection and control are therefore stimulating techniques to promote power system engineering. But, the effort that universities will put into those techniques depend more and more on the market demand. Indeed, most universities need some sort of sponsorship to put significant resources into new techniques. Therefore, manufacturers and utilities are a driving force behind the interest in power system engineering. A too conservative viewpoint from utilities creates a risk of the vicious circle: reticence towards adaptive techniques based on the fact that there are not enough competent engineers to assure their successful use, which will strongly undermine the interest for future students, so that the number of power system engineers will decrease further.

9.3 Higher knowledge base and different organization

9.3.1 Higher knowledge base

"Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically to make them more attuned to prevailing power system conditions". By analyzing this definition we can evaluate the change in knowledge we need for adaptive protections.

First there is "the prevailing power system conditions". Normally protection engineers are mainly concerned with the network in a transient state - the fault state - with limited attention to the network pre-fault state and the global scheme. Network calculations for protections often are simplified to a maximum extent in order to have a limited number of elements: the protected unit itself (line, transformer,..) ,an equivalent source at one or all terminals of the protected element, and of course the fault itself. The load is generally superimposed and the source impedance is kept constant. This point of view was certainly in use some years ago. Nowadays powerful fault calculation programs allow us to make more precise calculations, but protection engineers for the most part make the representation as simple as possible. Due to the habit of keeping it simple, there is a risk that they are now not capable of handling more complex representations of networks including for example loads, mutual coupling, tap changers etc. Additional training will then be necessary.

Adaptive protection techniques will undoubtedly evolve more and more to a "system" approach instead of an "element" approach. The protection engineers should be able to handle this. Not only fast dynamic change (faults) but also slow dynamic change (network condition) should be taken into account. Formerly, those changes were generally handled by different engineers in a utility dealing with theoretical aspects. This is already in the process of changing, as it has been suspected of being the reason for several regional black-outs. With adaptive protections that make full use of the knowledge on "the prevailing power system condition", this becomes a necessity.

A second part of the definition is "automatically". That means that information should be available to judge about the prevailing network condition. If this information comes from outside, communication is involved. The role of communication in adaptive protection is explained in Chapter 11. It can go from transferring a simple logical information without synchronization needs, to analog data with full synchronization. Therefore some knowledge in the field of communication will be required of protection engineers. The amount of data and the geographical distribution of it ,as needed for some adaptive features, will require dedicated point-to-point communication to evolve to shared multipoint communication. It implies a more difficult verification of fulfilling the dependability and security demands required by protection functions.

The information needed for adaptive features could also come from adjacent facilities. A lot of information can be extracted from the local control system. The data transfer between control system and protection will increase, and this will push manufacturers to integrate or coordinate the protection and control functions. There has been considerable discussion about integration-coordination of protection and local control at the symposium in Bournemouth [11]. Some reticence came out of that debate. However, now, 5 years later careful approaches to integration are taking place. The consequence is that the protection engineer slowly also enters the area of local control, a phenomenon already recognized by CIGRÉ 34 some years ago (CIGRÉ 34 changed its scope to "Protection and local control").

The definition of adaptive protection also includes the words "seeks" and "more attuned", which inherently express some uncertainties. Techniques suitable for handling these uncertainties should be used. Apart from the normal digital programming techniques, this will give rise to the use of Artificial Intelligence and all related techniques (see chapter 4). Even if it is accepted that the protection engineer needs only a basic knowledge of those techniques, the use of AI will certainly influence their way of thinking. It will be difficult to analyze the behavior of the protection as a function of external signals at the time of the fault. The "experience" of the protection in the past could influence the decision (learning by doing).

It is reasonable to expect that in the future, protection system data bases would be an important element of power system management systems. Such data bases are likely to contain Geographical Information Systems (GIS), power system network characteristics, the installed protection, metering, and control equipment information, protection equipment settings, etc. The data bases would be useful in many network performance studies, as well as in studies related to protection system design and maintenance. When adaptive relaying is in use, the engineering data bases must be updated as appropriate, so that the current settings, as well as the fall-back positions are always current. Unless this is done, post mortem analyses of system events would not be practical.

9.3.2 Different organization

If we see a computer reaching its limit we may change the hard disk, add RAM, or even change the processor. This cannot be done with people. We have to accept our limits. Therefore the increase in knowledge base discussed in 9.3.1 should be weighted against the effort needed to acquire it, to assimilate it and to use it. Also there should be a balance in the depth and the breadth of knowledge.

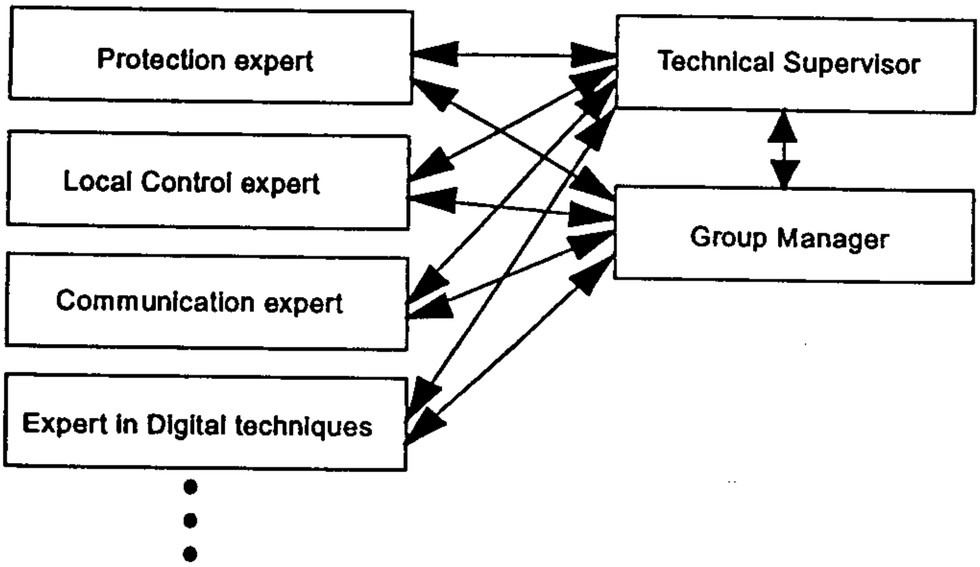

Figure 9.1: New organizational structure for protection and control engineering.

As being a protection expert (knowledge in depth) was already a full-time job in the past, it is clear that it would be difficult to demand breadth in all the other fields mentioned before. On the other hand, it is a necessity that someone can make the link between all these fields. Therefore the organization should be well adapted.

One possibility is the organization shown in Figure 9.1:

- a team of experts assuring the depth in each of the described fields
- a technical coordinator assuring the breadth, thus having basic knowledge in different fields and assuring coordination of all those fields
- a group manager leading the whole group.

The technical coordinator could be the group manager but the risk exists that there are too many management tasks to allow successful coordination on the technical side.

9.4 Restructuring problems

In a lot of countries restructuring waves are encountered mergers and economical competition. Generally there is a trend towards fewer personnel. The phenomenon has naturally nothing to do with the arrival of adaptive protections but it is interesting to analyze what the consequences are for the use of adaptive features.

On one hand, decreasing the personnel would be in conflict with the above mentioned increase of knowledge base. The system will become more complex, so more difficult to handle and control.

On the other hand the use of digital and adaptive techniques should lead to less human intervention:

- self-checking features decrease maintenance interventions.
- communication and monitoring possibilities allow better analysis without going on site and more specially for adaptive features.
- the adaptation is automatic, whereas in the past it was eventually manual.
- eventually settings are made easier due to less compromise.
- higher dependability leads to less abnormal incidents (requiring time-consuming analysis).

Therefore the influence of using adaptive techniques on the number of personnel should be negligible. Probably there will be a shift towards personnel with higher qualifications.

Although restructuring is generally driven by economical reasons, it is the responsibility of the technical staff to guide this restructuring towards a better structure to respond to the new technical challenges.

9.5 Training adapted to the level

Not everyone has to know everything about adaptive protection. It is clear that the protection engineer who calculates the setting of an adaptive protection has to know about power system dynamics and how to take into account the prevailing network condition, but the maintenance engineer can live with a practical knowledge about how to handle the protection. In a survey reported at the Antwerp colloquium about training [13], it appeared that the definition of a target group for training is very important. This was also recognized in a paper [14] were a new educational concept was proposed with a division of "function oriented topics". One hundred and eighty topics were recognized and it was suggested that each individual training program be based on the appropriate topics for the function.

It is not the aim of this work to propose a way of organizing training. There are too many organization related matters that differs from country to country. Here is an example of a possible training program:

FUNCTION	BREADTH	DEPTH	TYPE
Management-decision making	all fields	basic	commercial
Technical supervisor	all fields	medium	technical - function oriented
Experts	one field	in depth	technical - equipment & function oriented
Engineering & application	all fields	basic	technical - equipment & function oriented
Maintenance & commissioning	all fields	basic	blackbox - equipment oriented

Different emphasis could be placed depending upon whether it is a manufacturer or a utility, a big or a small company, and so on. Also people in higher hierarchical functions will probably have been in a lower function before. Example: a technical supervisor could have been expert or application engineer before. The individual training program should take this into account. It makes no sense to give a medium training program in the protection field if the technical supervisor was a protection expert before. The other fields should be emphasized.

In another paper [15] of the Antwerp session job rotation is also mentioned as a part of training.

9.6 Training tools

A course is a classical tool to train someone in adaptive protection. A theoretical course has nevertheless a limited impact. This was also the conclusion of the survey mentioned before [13]. People have generally no time to prepare and cannot assimilate the information at the speed it is given. Practical and personal training is therefore preferred.

For personal training good documentation is very important. People can assimilate at their own speed. But there is still one shortcoming: it is sometimes very difficult to know what is meant or going on. Then practical training can help. Having the protection and being able to test thoroughly it, is the most appropriate way to be trained.

Unfortunately, sensing an adaptive protection demand some special equipment. With the actual test cases it will be difficult to perform tests that put in evidence the adaptive feature. Those features are indeed generally based on additional logical or analog inputs. The test cases should also evolve in the future to be able to test some adaptive features.

Another possibility is to sense the protection by simulations. Powerful network simulation programs already exist on the market. It would be interesting to have additional protection simulation programs with which the performance of adaptive features can be verified.

9.7 Conclusions

It is emphasized in this chapter that the evolution towards adaptive protection is a natural and inevitable evolution. Evolution is a key point to keep a technical field attractive and power system engineering needs to be attractive in the present environment. An adaptive protection generally uses techniques that are traditionally handled by different experts. It will be necessary to adapt the organization to cope with that. In the chosen organizational structure it should be clear what is expected from each engineer. The training should be adapted to the level of the personnel and should take the functional description of the job into account. Finally, the necessary tools should available to guarantee successful training.

10. FIELD EXPERIENCES

10.1 Introduction

Six contributions on experiences with adaptive protection and control are presented in this chapter. Four are on the stabilizing protection, one is on locating EHV transmission line faults, and one is on distribution line protection.

Section 10.2 (Japan) and 10.7 (the United States) are about real-time prediction stabilizing protection. The protection predicts out-of-step with real-time calculation using voltage and current data during disturbances, and initiates the necessary remedial actions, that is load or generator shedding or intentional islanding. The protection of section 10.2 once successfully saved a nuclear plant from scrambling. The protection of section 10.7 has not yet encountered an unstable power system condition, however, it has produced correct characterization of all stable swings.

Section 10.3 (Japan) is about lost-power compensation stabilizing protection. Originally, the protection calculated required load or generator shedding power based only on pre-disturbance transmitted power and generated power, then initiated the load or generator shedding. Based on experiences with several shedding operations, the protection added two functions for more adequate shedding. The functions were 'dropped load compensation' and 'supplementary shedding' dependent on frequency deviation. The protection experienced four successful operations, and four correct but unsuccessful operations.

Section 10.6 (France) is about the technical feasibility test of out-of-step protection that discriminates out-of-step with a global view obtained by comparing the voltage phases of all elementary areas. It then initiates the necessary remedial actions. The test proved that the protection was valid.

Section 10.4 (Japan) is about locating EHV transmission line faults. The locating error due to interactions of fault resistance and load current is reduced by compensating pre-fault load currents. The distance measurement errors of 34 out of 42 locations at which fault points were identified were less than 1 km.

Section 10.5 (the United States) is about overcurrent protection that allows the instantaneous unit to trip only during stormy or lightning weather when faults are usually only temporary. This function reduces momentary outages that customers suffer by permanent faults, however, no experiences are described.

Protection functions in Sections 10.2, 10.6, 10.7 and 10.3 rely upon telecommunication links, and the former two utilize simultaneous sampling. The system of 10.7 uses synchronized sampling and phasor measurements. These protection functions need excellent availability and reliability of the telecommunication links.

From all the contributions reported, it seems that experiences with adaptive protection and control including telecommunication links have been satisfactory.

10.2 Experience with real-time prediction type stabilizing protection systems[3,17,23]

The Tokyo Electric Power Co., Inc. (TEPCO) uses real time prediction type stabilizing protection, that predicts out-of-step by using the change in generator output power from before the fault and remedies the condition which may lead to an out-of-step during the evolution period. The protection was first applied to ten generators in nuclear plants in 1986, and as of the end of March 1995, to 43 generators with a total capacity of 31400 MW.

TEPCO is satisfied with the operation experience of the protection. One successful operation and one unwanted operation were experienced as of the end of 1994. The successful operation saved a nuclear plant operating at 3300 MW from a scramble, while the condition causing the unwanted operation was corrected immediately.

10.2.1 System configuration

The protection system operates as follows:

- Internal phase angle differences δpr(0), between generators (including generators in pumping mode) located far away from each other are continuously observed.
- Generator angular velocity changes, Δωk, caused by faults are calculated by using the differences in generator output power from the pre-fault value.
- Generator internal phase angle changes from the pre-fault value, δ(tp), at predetermined time tp (usually 240 ms) later are predicted by using Δωk.
- Internal phase angle differences, δpr(tP), between generators after tp are predicted with δpr(0) and δ(tp).
- If some of δpr(tP) are above the corresponding threshold level δL, an out-of-step is predicted, and the internal phase angle difference δpr(tP)* after tp when some of optimum generators for correcting the predicted out-of-step conditions are shed is calculated.
- The system initiates shedding of the minimum number of generators that would satisfy $\delta \leq \delta L$.
- L is determined for each phase angle difference with off-line stability calculations.
- Necessary data for calculating δpr(tP) and δpr(tP)* are transmitted by duplicated microwave links passing through different routes.
- Tripping is subject to the operation of the power system disturbance detector, which detects change in frequency or power so that it will be free from false tripping while the power system is in normal operation.

10.2.2 Successful operation

Figure 10.1 illustrates a power system performance with successful operation of a protection system. The three generators of a nuclear plant generated 1,100 MW each, and the generated power was transmitted via a 500 kV, double-circuit power transmission line, 106 km long, to a bulk power system having a total generated power of about 40,000 MW.

Double-circuit faults occurred in phases a and b of circuit 1 and phase a of circuit 2. Because this transmission line was provided with segregated differential protection and was under single and multi-phase automatic reclosing, the faults were cleared by tripping breakers on only the faulty phases, leaving phase c of circuit 1 and phases b and c of circuit 2 connected.

At 185 ms after removal of the faults, the nuclear unit generating 1,100 MW, shown in Figure 10.1, was shed by operation of the stabilizing protection system. At 1,230 ms after removal of the faults, all tripped phases of the transmission lines were automatically reclosed successfully, thus permitting continuation of stable operation. There was a frequency of about 0.8%, and the shed nuclear unit was brought into parallel operation in 44 minutes.

The solid line in Figure 10.2 represents the results of simulating the internal phase angle to a remote generator and the output power of the generator saved by this operation. The faults began at time T0, and were removed at time T1. Generator shedding occurred at time T2, and automatic reclosing at time T3. If generator shedding had not been performed, the power and

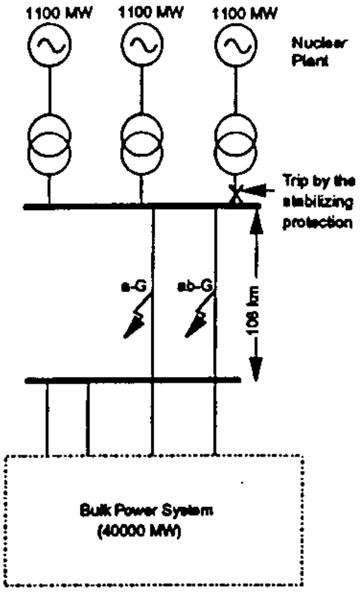

Figure 10.1: Power system in successful operation.

internal phase angle would have changed as shown by the broken line, and would have been detected as a step-out.

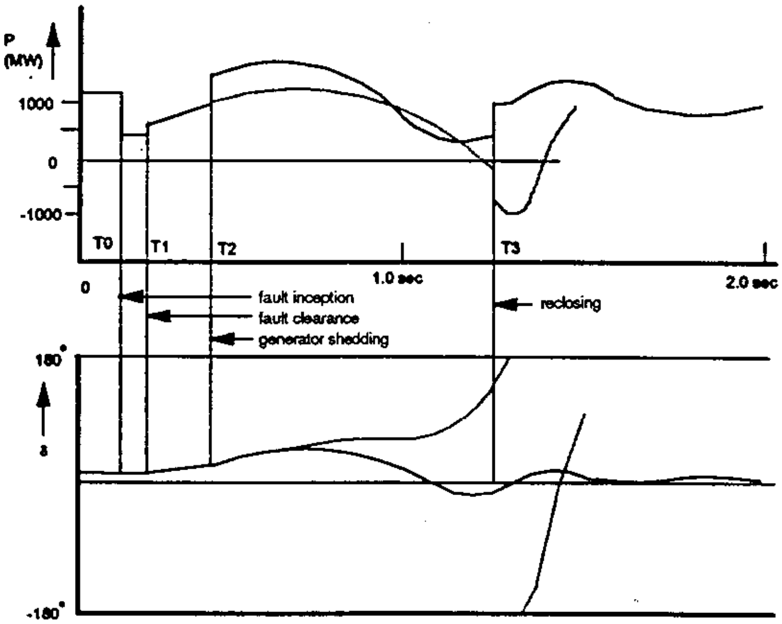

Figure 10.2: Output power and internal phase angle difference of generator relieved by generator shedding.

10.2.3 Unwanted operation

The unwanted operation was caused by a single-phase tree fault, which was removed by phase comparison protection at high speed. However, the power consumed by the tree in contact increased from the normally transmitted power of 5,962 MW to 6.492 MW during the fault.

The stabilizing protection system erroneously took this 6,492 MW for the power transmitted prior to the fault, judging that the power transmitted after removal of the fault decreased. This caused the system to predict an abnormally large internal phase angle difference in the generator and thus to initiate generator shedding.

This defect was remedied immediately after the unwanted operation. After that, neither unwanted operation nor failure to operate has been experienced. Two relatively large power swings have been experienced but the internal phase angle differences were predicted correctly.

10.3 Experience with one formula for lost-power-compensation type stabilizing protection systems[3,4]

Chubu Electric Power Co. (CEPCO) has applied one formula for lost-power-compensation type stabilizing protection to the major part of its power system since 1968. The protection was first implemented with analog electronic devices, and was refurbished with digital devices in 1978. Furthermore, the protection has been improved with the expansion of the power system and with the progression of digital technology.

10.3.1 System configuration

The protection system operated originally as follows:

- Information on transmitted power on the main power transmission lines and generated power of main power plants is continuously acquired during power system normal operation.
- If a power system is accidentally separated by a disturbance, the unbalance power P_{UB} between load and required generation of the separated power system is calculated based on the pre-disturbance transmitted power.
- The required load or generator shedding power P_{SH} is calculated based on P_{UB} and the generating capacity of the separated power system.
- Required tripping to ensure generator shedding or load shedding close to P_{SH} is initiated.
- Necessary information for calculating P_{SH} is transmitted by duplicated microwave links passing through different routes. Although numerical information would be transmitted prior to a disturbance, only on-off information is transmitted at the occurrence of a disturbance.
- Tripping is subject to the operation of the power system disturbance detector, which detects changes in frequency, so that it will be free from false tripping while the power system is in normal operation.

Based on experiences with several shedding operations, the following functions are added to the original functions in order to perform more adequate shedding in 1987.

Dropped load compensation: The dropped load P_{DO} of the separated power system is estimated dependent on the EHV substation busbar positive sequence voltage measured during fault and total load in the separated power system. The unbalanced power P_{UB} is corrected with the estimated dropped load P_{DO}.

Supplementary shedding dependent on frequency deviation: Shedding of part of the required shedding power P_{SH} is initiated in the first phase, and supplementary shedding is initiated dependent on frequency deviation and change and P_{SH} in the second phase.

10.3.2 Operation experiences

On the protection mentioned above, four successful operations and four correct but unsuccessful operations were experienced. No unwanted operation or failure to operate has been experienced. The unsuccessful operations referred to an islanded system that became so small as to cause the conditions described below, which made it impossible to continue stable operation despite correct initiation of generator or load shedding.

- The islanded system had a load too small for the unit generator capacity, and even with generator shedding the frequency rose too high on all except one generator, which was kept in operation.
- The generator capacity of the islanded system was so small that the loads were too great for the generator capacity despite the shedding of all loads that could be shed.

10.4 Experience with fault locating using load current compensation for reducing errors[5,20]

One field experience with fault locating using an adaptive feature to reduce measurement errors with fault resistance, using an in-fault current that was compensated for the prefault load current was reported by an electric power company. The power company had installed digital protection equipment providing fault locating function for 93 terminals on EHV transmission lines as of the end of March 1992, and had experienced 50 fault locating actions.

This fault locating function uses the following equation to reduce measurement errors caused by fault resistance:

$$L=Im(Vt\ If^*)/Im(It\ Z\ If^*)$$

where L = distance to a fault; Vt = terminal voltage; It = terminal current; Z = transmission line impedance per unit distance; If = Idf-Ibf;.If^* = conjugate complex of If; Idf = terminal current during the fault; Ibf = terminal current before the fault; Im(.) = Imaginary part of (.).

Fault points were identified for 42 of these 50 cases. Table 10.1 shows the measurement errors per average length of 50 km of the transmission line to which it was applied. The digital protection equipment identified all the faults that had occurred with its built-in fault locating function. With its high accuracy and excellent record the fault locating function is useful for speedy recovery from faults and saves labor in the maintenance of transmission lines.

Table 10.1: Range Measurement Errors

Error	*Number of Faults*
0 to 1 km	34
1 to 2 km	2
2 to 3 km	2
over 3 km	4

Note: of the 4 faults with an error of over 3 km
*1 one was due to ignoring intermediate infeed from a small-capacity power plant;
*2 the other three were all located with an error of over 3 km. Two of these occurred with the same device at about the same distance to the fault (100 km) and about the same error (5 km).

10.5 Experience with Distribution Relaying

Centerior Energy (previously Cleveland Electric Illuminating - CEI) located in Cleveland, Ohio, adapted its distribution relaying to changing weather conditions. This was done to reduce momentary outages experienced by customers with sensitive electronic equipment. Previously it had been CEI's practice to provide instantaneous tripping to reduce the number of permanent outages caused by temporary faults. This was also an attempt to apply fuse-saving techniques and avoid costly and time consuming fuse replacement. This practice allowed feeder relaying to instantly trip the feeder breaker once the fault is detected and to reclose the breaker with the chance that the fault is gone, before allowing field fuses to blow. If the fault was temporary, a momentary outage was experienced by all customers on the feeder, versus a permanent outage that would have been experienced by all customers on the load side of the fused circuit. Past sensitivity studies indicated that this was a preferable practice. Due to changing technology, however, distribution loads now include digital microprocessor-based equipment. Customers are now sensitive to momentary outages as well as permanent ones. The adaptive relaying application is an attempt to optimize the protection by using instantaneous trips only when it is needed most, that is during storm/lightning conditions when faults are most likely temporary.

The digital protection relays used on distribution circuits have the capability to change their settings via SCADA control. This capability allows a dispatcher, at the control screen, to easily change feeder protection from one set of preprogrammed settings to another. From the control screen, via SCADA, the INST function is disabled during good weather ("Normal" settings) and enabled during bad weather ("Storm" settings).

10.6 Experimentation of a 400kV-grid self-adaptation system preventing grid voltage breakdown under synchronism failure

Electricité de France (EDF) is implementing a protective plan to impede any 400kV-grid collapse process, acting through both load shedding and the separation of areas undergoing losses of synchronism.

The processes involved in grid collapse are the following :

- overloading of grid components (lines, transformers...), which results in load transfers;
- voltage and frequency collapse events;
- loss of synchronism.

To avoid the occurrence of such processes, remotely-controlled safety actions are started which, nevertheless, may not be efficient enough or too slow to prevent a collapse process from developing. At that point, load shedding and area islanding are automatically carried out.

Up to now, load shedding has been based on local frequency-related data (4 15%-load steps at: 49 Hz, 48.5 Hz, 48Hz and 47.5 Hz) and the area islanding depends on the local detection of voltage beats induced by losses of synchronism (line breaker opening at the 1st, 2nd, 3rd or 4th beat).

Several significant incidents have proved these measures to be inadequate. So, a new protective system is being developed.

The principle of loss of synchronism detection implies that, at a central point, phases of equivalent voltages measured at stations located in the middle of the electric system 'elementary and homogenous areas' are compared instantaneously.

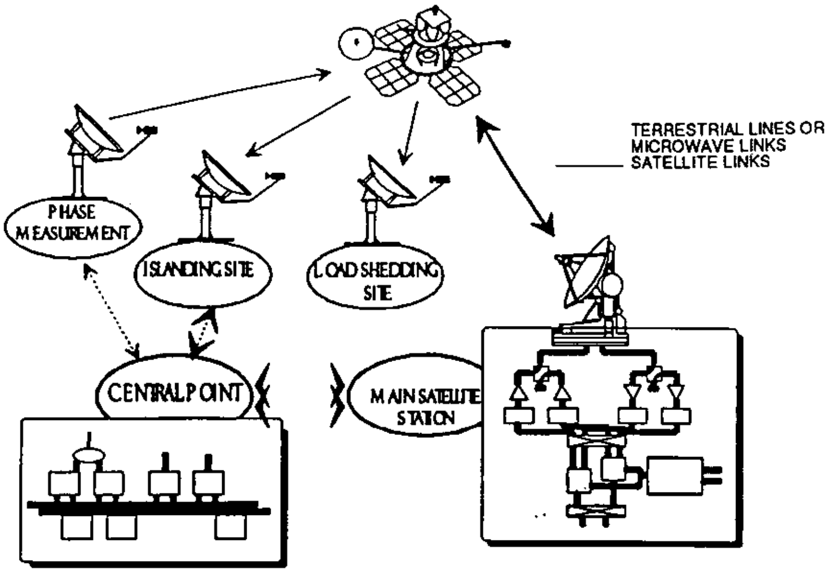

Figure 10.3: System Scheme.

This system includes a decision center (central point) which obtains a global view of the electric system as a whole, by comparing the voltage phases of all elementary areas, in real time.

Whenever a phase variation typical of loss of synchronism occurs, two types of commands are issued:

- line remote-trip, to island the area out of synchronism:
- partial remote load-shedding (at medium voltage level) where such action appears necessary in the system, according to the power imbalance of the area affected, and the strength of the interconnections.

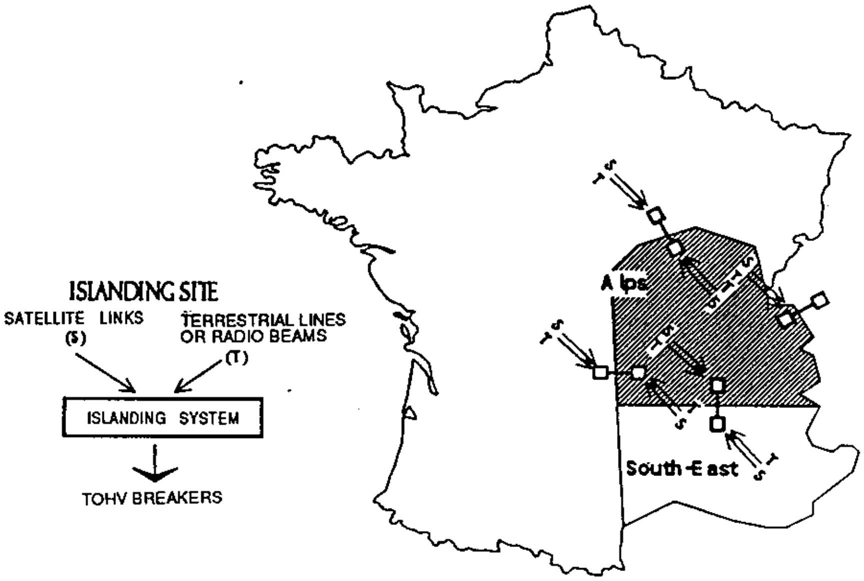

Figure 10.4: Islanding Function.

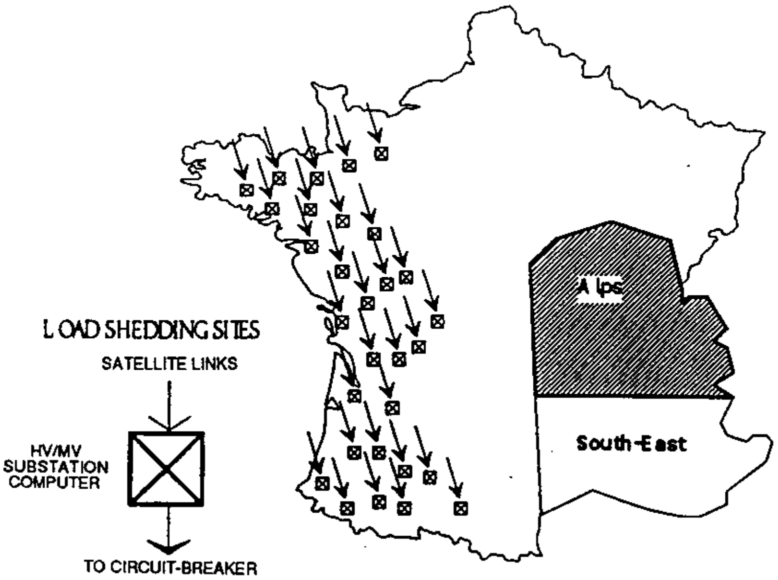

Figure 10.5: Load Shedding Function.

Self-adaptation of the grid to its operating conditions is thereby achieved.

Real-time comparison of voltage phases needs a single time reference for them all. That is why synchronization signals are sent periodically to every measurement point. The system's overall response time (which includes times for measurement, loss of synchronism detection, transmission and circuit breaker opening) shall be less than 1.3 seconds. This protective system shall offer a very high degree of dependability (one unexpected incident every 1000 years and one failure every 1000 actuations). To achieve such a dependability, the communication system is duplicated (terrestrial links through microwave and satellite links), the central computer is partly redundant and local trip commands are validated by local voltage variation criteria, a few seconds before commands are received.

The satellite transmission system provides measurement synchronization within 50 microseconds. The protective plan efficiency has been checked through a great number of numerical simulations applied to a dynamic model of the grid. The technical feasibility of the plan was tested within the grid, without satellite links or tripping, it involved five measurement points equipped with specific phase meters and a host computer. The experiment proved that the principles of the protective system were valid and it allowed some options such as the central point "real-time" algorithm to be validated. Satellite links established on VSAT (Very Small Aperture Terminal) networks were tested separately. The maximum spread observed as regards synchronizing pulses amounted to 15 microseconds. Besides, the overall response time measured was 630 milliseconds. The satellite link performance meets the protective system requirements. The first stage of the system, as applied to two strategic areas regarded as priority areas, shall be operational by 1996. Three 400 kV-stations in each of the two areas will be equipped with two phase meters. The related coordinated load shedding (about 5000MW) will be performed in two other areas as shown in Figures 10.3-10.5.

In the future, the implementation of such systems should protect a whole region, and possibly the entire country, against any system collapse.

10.7 Adaptive Out-of-Step Relay[6,10]

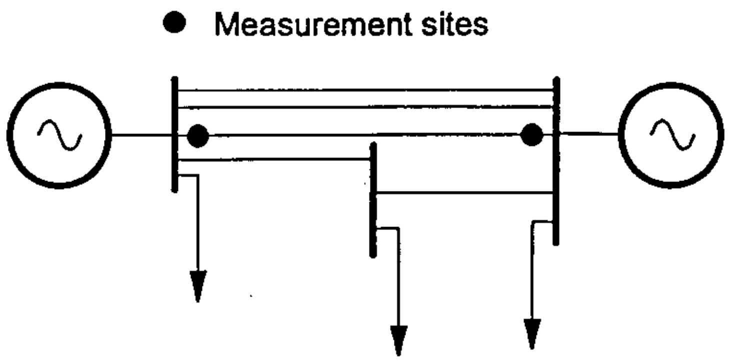

Figure 10.6: Equivalent two-machine system for adaptive out-of-step relaying.

Out-of-step relaying has been an important protection function for an interconnection between two utilities in the south-eastern United States. A recent research project developed an adaptive out-of-step relay, and an experimental system was installed in the field. The installation has been in service for about one year, and remains in a monitored mode. It is expected that this installation will be used primarily to prove the concept, and may lead to commercial developments, which can be used for actual out-of-step tripping and blocking tasks.

The field installation consists of two relay systems installed at each end of a 500 kV transmission line. Each system is made up of a synchronized phasor measurement unit which measures the complex positive sequence bus voltages and line currents, and records the precise instant when the measurement is made. The simultaneous phasor measurements from the two ends of the transmission line in conjunction with an appropriate two-machine equivalent circuit (see Figure 10.6) are used to set up an equal area computation when a transient stability oscillation is detected. As shown in Figure 10.7, it is first necessary to determine the post-disturbance state of the system, before the equal area criterion can be applied. The disturbance in question could be the loss of an important tie-line, which is detected by the status of circuit-breakers and switches at the measurement site. Alternatively, the disturbance may consist of a loss of generator in one of the systems. The generator loss is estimated by observing the swing in progress for a short time - of the order of 0.25 second. When a valid disturbance model is obtained, equal area criterion is applied to determine whether the swing will be stable or unstable. An appropriate blocking or tripping signal can then be generated and communicated to the pre-selected sites.

The installation has been in place for about one year. The relay system has not been connected to implement its control decisions, and remains in a monitoring mode. During this period, all transients which occurred happened to be stable, and the relay produced correct characterization of all the events. No unstable swing has taken place as yet.

A number of improvements have been made while the relays are installed in the field. The most interesting of these is the development of an automatic procedure for adjusting the dynamic parameters of the two machine equivalent with real-time swing data, so that accurate prediction of swings could be made. Work on these developments is still in progress.

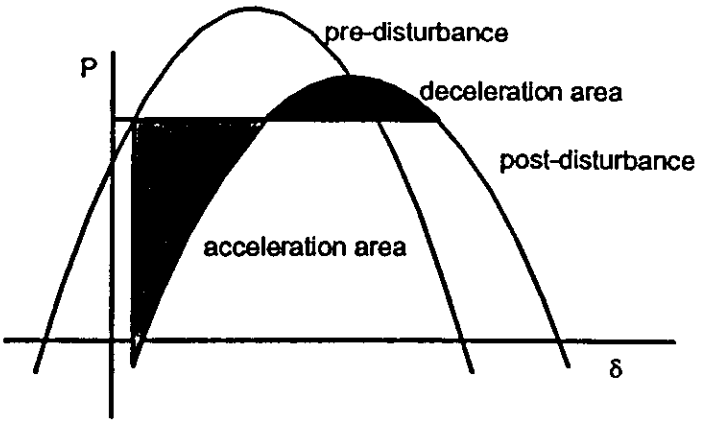

Figure 10.7: Equal area criterion applied to the two-machine equivalent system.

11. ROLE OF COMMUNICATIONS IN ADAPTIVE RELAYING

11.1 Introduction

Communication is not a goal in itself, it is a means to transfer information between distributed logical equipment. Equipment and processes are distributed for various reasons:

- Most important is the nature of the electric power system itself. Electric power protection and control is distributed inside a substation, between substations, between substations and control center, or between control centers. For adaptive protection depending on weather forecast, it is even necessary to merge information from a meteorological center.
- Dependability of the system is also very important. Even when it is possible to gather all information in one equipment, dependability is usually insufficient. Distributing the processing allows the system to be fault tolerant: for example, two protection relays are installed for each line terminal. To take full advantage of the distributed processing it is advantageous to make the devices communicate, and exchange results of calculations: for example, distance protection relays at each terminal of one line communicate to give blocking orders.
- One of the reasons to use communication may be technological: one device does not have enough processing power, therefore the processing must be shared; or existing 'approved' devices need to be re-used in a new application without redeveloping them (because it is costly and time consuming to certify and approve new devices).

Communication to a protective relay can be performed in different ways. Besides the serial communication links, binary inputs may also have to be used e.g. for switching between prepared sets of settings. An advantage of this principle is that the relay engineer can check completely the performance of the protection with various settings. If decision for adaption is taken within a station, the wiring can be used to give the signals for adjustment of configuration and of settings to the relays. This principle is also applicable in conventional stations without computerized substation control. The new numerical relays offer this facility and the concept at the moment seems to be accepted by a number of power utilities.

Communication, like adaptive protection, is not a new concept. But it will be employed at an accelerated pace in the future, due to the evolution of the digital and distributed system technology. Adaptive protections are natural users of communication, since they have to use external information to improve the way in which they are working. Conversely, knowing that communication is available between relays will help define new protections algorithms.

In order to correctly size the future communication networks, it is important to define today the needs for the new applications in distributed protections.

11.2 Communication context

Figure 11.1 gives a synthetic description of the communication context from the protection device point of view.

Following entities are of concern:

- A Substation, divided into three functional parts, namely Protection, Control and Apparatus. These functions are generally performed by separate devices, and can be designated by bays.

- A Network Control Center, divided into two functional parts, Protection and Control. These functions are performed by different people, dealing with computers and communication links. A Network Control Center may be divided into several areas (regional, national for instance), but cab be considered to be a black box.
- A Remote Substation, it has the same capabilities as a substation.

Communication between the entities are:

1. Links with protections from remote substations.
2. Links with the apparatus of the bay.
3. Links with the local control of the substation.
4. Links with a Network Control Center.
5. Telecontrol links, between a Network Control Center and the local control of the substation.
6. Links inside a Network Control Center, in order to use control information for adaptive protection purposes.

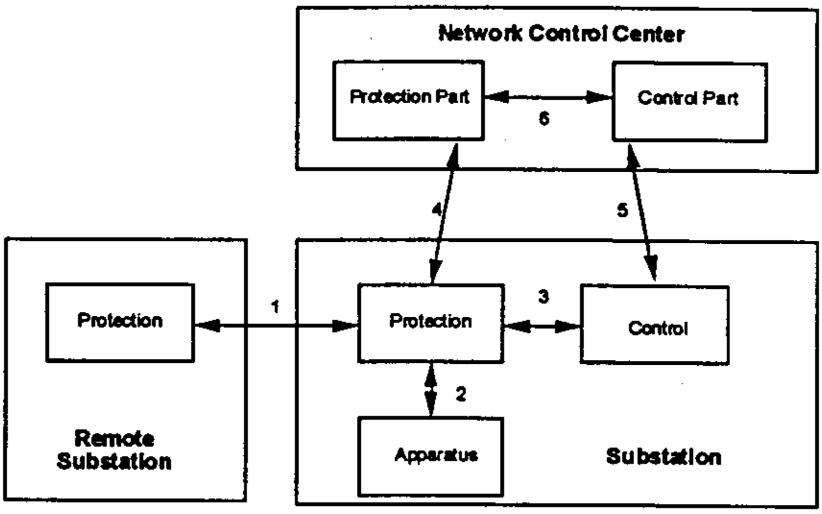

Figure 11.1: Communication Context.

11.2 Technology

Adaptive protection requires automatic actions to fit power system conditions. It needs closed loop arrangements, that will use the communications links described above. They will depend on the location of remote data sources, the data exchanged, and the existing equipment. For a given cost, the amount of information that can be exchanged decreases when the distance between nodes increases.

11.2.1 Binary communication

Binary information is traditionally exchanged on links 1, 2 or 3 through simple point-to-point wiring. This is sufficient for blocking orders and setting selection, but is too limited for more sophisticated adaptive protections where more data must be exchanged or when 1-to-N communications are required (see later). Other drawbacks include the cost of a reconfiguration of the links and the limited self-supervision of the links.

On the other hand, this type of communication is very fast (transfer is nearly instantaneous for short distances), and will remain a cost effective solution compared with digital communications if the transmission time must be very short.

11.2.2 Digital communication

Digital communication technology has greatly improved during the last 10 years, and is now capable of covering nearly all types of links (refer to Figure 11.1):

- For instance, link no.1 used in line differential protection requires the exchange of instantaneous currents: modern solutions use digital 64 kbps links between the substations.
- Link no.2 is rarely digital. Non conventional (optical) transducers and apparatus health monitoring will utilize this link. Digital currents and voltages of the different bays will be distributed inside the substation in the future, and new adaptive protection principles may be developed. Speed of the network will be several Mbps.
- Link no. 3 is used for integration of protection and control functions. The protection may send supervision information, disturbance files, time-tagged events, etc. It may receive settings, time synchronization, etc. Speed of the network varies between 1200 bps and 1 Mbps.
- Link no. 4 is a new one, primarily employed by protection maintenance people at the Network Control Center. This link may be used for adaptive protection, when a quick transfer is needed from the NCC to the protections, (for example, see Sections 3.5 and 3.11).
- Link no. 5 is used for telecontrol purposes. Speeds are slow, no more than 19.2 kbps.

As it is a new technology, the area of digital communication is still lacking standards. Basic de facto standards do exist, defining for instance the speed and the share of the network among subscribers: Modbus (10 kbps), Bitbus (100 kbps), FIP/ISP (1 Mbps), Ethernet (10 Mbps), FDDI (100 Mbps).

These standards are insufficient to totally describe the communication between the different subscribers of the network: the syntax and semantics of the messages exchanged must be defined. Without a common language, the solution is specific to one manufacturer.

Emerging standard solutions are based on IEC 870-5 and IEC 870-6 documents:

- Link no. 5 is fully described in the IEC TC 57 T101 profile.
- Some proposals for standardization of link no. 3, based on IEC 870-5 documents are currently being reviewed in IEC TC 57 working groups. However, the communication only takes place between a protection system and a Man Machine Interface. It may not be adequate for adaptive protection because the speed is too slow and the language is too limited.

11.3 Definition of the needs

Table 11.2 summarizes the needs for the examples given in chapter 3. A first step in defining the needs consists in specifying the following information, for each adaptive function. One can see that:

- There is a need to strongly develop link no. 4. Note that the decision taken at the Network Control Center will probably be based on information coming from link no. 5. There are two classes of needs:

1. Some applications have time critical delays (<0.5 s), such as stability protection. As the speed and cost for long distance digital communication is low, compromises between cost, security and room for growth will have to be made (see next paragraph). Gateways between different networks, translating one language into another, will have to be avoided.
2. Other applications may share existing telecontrol links, eventually with another language.

- Transmission time on link no. 3 may also be divided into 2 classes:
  1. Some applications may use the existing standard networks, based on IEC 870-5, where the transmission time is more than 1 second.
  2. Other applications require a new type of network, both in technology and language.
- There is a need to have a "1-to-N" communication, N is up to 100. OSI model is limited to point-to-point communications, because it fits the majority of the needs and limits the complexity of the protocol. Compromises between security, cost and time must be developed to cope with this need.

Function	Link	Quantity	Time
Remote Back-Up Zone of Distance Protection	1	1 real	10 s
Distance Relay at Transfer Bus	3	1 integer	2s
Transformer Differential Protection at Transfer Bus	3	1 integer	2s
Adaption of fault detection level of line prot.	4	1 real x 10 prot.	4 s
Power swing detection and control	4	1 integer x 5 prot.	0.5 s
Generation protection during Fast Valving op.	3	1 integer x 5 prot.	0.5 s
Network condition restoration	4	1 integer x 100 prot.	4 s
Network Voltage Emergency Conditions	4	1 real x 10 prot.	60 s
Mutual compensation on // lines	1	1 integer x 4 prot	4 s
Real time stabilizing protection	3, 4	1 integer x 2 prot	0.2 s
On line stability protection	4	1 integer x 5 prot	0.2 s
Adaptive conversion of protection in cases of partial protection system failures	1,4	1 integer	4 s

Table 11.2: Examples of chapter 3.

11.4 Transmission time

Transmission time of the information must be studied carefully: it is the time required to reach from one protection function to another, not merely the time of transit on the physical medium of the network. Figure 11.2 shows the transmission path of information between two subscribers of the network (A and B) connected through a Gateway. For example the Network Control Center, B is a protection function, and the Gateway performs a conversion protocol. The gateway will be used because the initial design of the protection may not have included the Network Control Center.

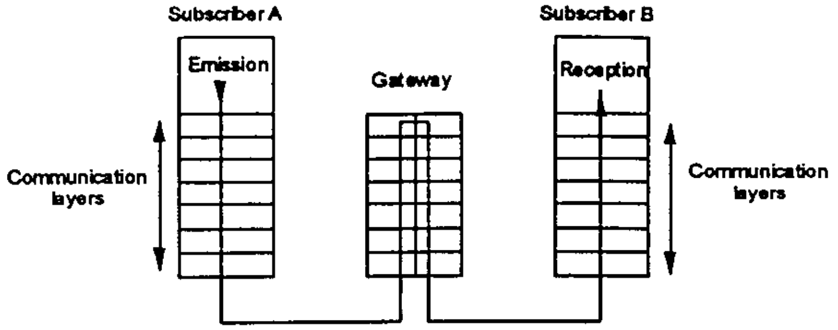

Figure 11.2: Transmission time.

Transmission time includes:

- Latency of the communication layer tasks in A, B and Gateway. This is dependent upon the operating system of each device, from 10 µs (real time kernel) up to 50 ms (UNIX for example).
- Crossing of the communication layers, in A, B and Gateway. This is dependent upon the protocol, of its implementation (copies of buffers between communication layers, use of a communication card, use of different tasks for the communication layers), and of the resources of each computer (processing power, memory size, DUART). For each device, this time will vary between 10 ms and 1 s.
- Crossing the network itself. This is only dependent on the size of the message and the speed of the network. Message means the total number of bits sent on the network, and not only the raw data mentioned in the previous paragraph.

11.5 Quantity of data

The real amount of data exchanged on a digital network will be much more important than the raw needs for different reasons: security, availability and capability for evolution. Compromises with time and cost will have to be made too. Specification of an adaptive protection have to take decision for each item.

11.5.1 Security

The data must to be encoded to avoid maloperation: typically a 16 bits cyclical redundancy code may be used. If the CRC is wrong, the receiver will send a negative acknowledgment and wait for a new value.

However, for time critical data, re-transmission of wrong information may not be possible. In this case, the code must contain the information sufficient to reconstitute the original data. This is used in the French Defense Plan for On Line Stabilizing Protection.

In a 1-to-N communication, acknowledgment takes even more time (N messages). Moreover, management of a negative or of an absence of acknowledgment is complex if the objective is to maintain a coherent system: is it acceptable to change the setting of one protection, if the other coordinated one is inaccessible by the network ? It may be better to come back to the previous situation, in this case.

If data is coming too late (because of transmission problems), it may lead to maloperations, and it may be better to forget it than to use it. Addition of a code in the command is a means to control the use of old data, and is used for example in ARTERE (telecontrol network from EDF). Of course, both systems must have a common synchronization reference.

To avoid the intrusion of external communication units, different means may be used: encryption of data (at each exchange), use of a password (at the initialization time only or at each exchange).

11.5.2 Availability

In order to be sure that the communication link is healthy, information must be exchanged even if there is no need to transfer operational information. The exchanges will take place inside a logical connection, which has to be opened first. Of course, this requirement may be very costly.

11.5.3 Evolution capability

Distributed processing is a relatively new concept, and all the applications are not yet known yet. What has been understood is that the protocol should contain mechanisms to cope with new undefined requirements. The list below (extracted from IEC TC95 WG6 work) gives some examples of overheads of the communication systems, required to reach this objective. Note that for real time data, this overhead will occur only at the initialization of the communication.

- Real-time data (as opposed to data exchanged between a Man Machine Interface and a Device) are exchanged through a client-server mechanism: during an initialization phase, clients will ask the server which data they want to receive to perform their algorithm (subscription), how (format at the application layer) and when (cyclically or immediately after a change, normal or express transmission). The name of the data needs to be standardized to permit cooperation between devices from different manufacturers. The client-server mechanism will be standardized as a generic one (independent from the application).
- Compatibility between versions of software and database of the communicating partners is checked during the initialization. Each device will learn from the other what its capabilities are, so that the other knows how to communicate with it (type of acknowledgment, capability for having its setting changed in a dynamic way, for example).
- Man Machine Interface data are self descriptive so that an operator is able to interpret them. This avoids the need to standardize the names of all the data of all the devices.

11.6 Conclusions

In summary, defining the communication needs for adaptive protection requires these steps:

- Write a complete specification at the ***system level***, that is assuming that their is no distribution of the function. Example is that a new setting should be dynamically used by a protection, without interruption of service.
- Distribute the function according to the location of the different devices. Add new specifications for communications: raw volume of data, security (CRC, acknowledgment, intrusion), availability, capability for evolution (standardization of names, overhead at the initialization phase).
- Specify the tests, including inter-operability tests, if the function is split among devices from different manufacturers.

- Select the appropriate network. If the existing ones are to be restricted, implementation of this new function may justify a new one. Integration of protection and control functions will facilitate that choice.

12. SUMMARY AND CONCLUSIONS

1. The working group has discussed and adopted a definition for adaptive relaying and local control as follows: *Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions.* This report has explored the possibilities offered by modern technology to make protection and control systems adaptive in the sense of this definition. It is noted that adaptive protection and control systems can be most easily realized through the use of computer based relays and control systems. The industry survey conducted by the working group reveals that the relay engineers fully recognize the opportunities offered by adaptive protection principles. The survey has pointed out many opportunities for adaptive protection, which have been cataloged in Chapter 2 of the report. Although a large number of suggestions for adaptive functions have been judged to be interesting and desirable, it is found that there is considerable difference of opinion among the responders about the possibilities of practically achieving the proposed adaptive solutions.
2. It seems certain that communication links are essential for full realization of the potential offered by adaptive relaying concepts. Many responders and the working group members feel that the fiber-optic links are likely to play a greater role in many traditional relaying functions, and will certainly facilitate the implementation of adaptive relaying concepts.
3. As the communication systems become more and more important to the protection and control functions, the need for standardization of interfaces becomes acute. There are no applicable universally accepted standards for relays and communication systems. Several manufacturers and utility companies have been working towards *de-facto* standards for various interfaces. The subject of adaptive relaying further underscores the need for such standards, as has been well recognized by various national and international standard-making bodies. It is hoped that appropriate standards will soon be forthcoming.
4. The benefits to be gained by using adaptive relaying concepts can be discussed qualitatively. However, it seems quite difficult to quantify the benefits, a step that must be taken before economic benefits of using adaptive features can be assessed. Implementation of adaptive features in relay systems is likely to be determined on a case-by-case basis. As with most new technologies, a period of promising or successful field trials is needed, and from an account of existing adaptive systems included in this report, the industry seems to be in the process of gathering such experience.
5. Chapter 5 discusses the failure modes of an adaptive protection system. This is offered as a case study, and evaluations of this nature must be carried out before an adaptive feature is implemented for field use. The possibility of failure of the communication system, which is an integral part of any adaptive protection and local control system, must be reckoned with. If the communication system fails, the protection system must fall-back upon its non-adaptive settings. It may be necessary to force other neighboring adaptive protection systems into their fall-back positions as well, as coordination between neighboring systems may depend upon the settings currently in use by the adaptive protection system whose communication system has failed.
6. The working group has also considered the need for testing the adaptive relay systems, and training the prospective users of such systems. It seems clear that many of the training tools

developed for traditional analog and digital protection systems are directly applicable in this new technology. Furthermore, since adaptive protection systems may impact the operation of several neighboring protection systems with which they coordinate, it may be necessary to develop tests which simulate various conditions on larger portions of a power system. These ideas have been discussed in Chapter 8 of the report.

7. The working group notes that the number of publications in the field of adaptive relaying has been increasing at a very rapid rate during recent years. A bibliography of publications known to the working group has been included in Appendix IV of the report.

The working group hopes that this report will acquaint the protection and control engineering community of important opportunities to be explored with the concept of adaptive protection. As these ideas evolve, it is likely that the distinction between the protection engineering function, and system operation and control engineering function will become blurred. It is possible that the internal organization of utility companies and manufacturers may have to adapt to make the best use of the opportunities that this technology brings. It is a challenge posed by the technological advances of recent years, which the electric power industry of the future must meet.

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Appendix I

CIGRÉ STUDY COMMITTEE 34

Working Group 34.02

ADAPTIVE PROTECTIONS

INDUSTRY SURVEY

Part 1: Responder's particulars

Part 2: Adaptive protections survey

ADAPTIVE PROTECTIONS SURVEY

Part 1

Respondents particulars

1. RESPONDENT: Please give particulars about yourself in the following space.

Country: ______________

Respondent's Affiliation:

- Utility ☐
- Industrial ☐
- Cogenerator ☐
- Manufacturer ☐
- A/E or Consulting ☐
- Academic Institution ☐
- Other ☐

Responsibility:

- Purchase & Specification ☐
- Installation ☐
- Maintenance ☐
- Testing ☐
- Setting & Coordination ☐
- Performance Analysis ☐
- Other ☐

Job title:

- Chief Engineer ☐
- Supervising Engineer ☐
- Staff Engineer ☐
- Engineer ☐
- Professor ☐
- Other ☐

Field of Activity:

- Generation ☐
- Transmission ☐
- Distribution ☐
- Supervision & Control ☐
- Construction ☐
- Research ☐
- Special Services ☐
- Other ☐

Number of years experience with protective relaying systems: ______________

2. **UTILITY DATA:** If you work for an electric utility, please provide the following data. Otherwise, go on to question No. 3.

Peak Load (MW): ______________

Circuit voltage	Transmission Lines (km)	Cables (km)
a)	_______	________
b)	_______	________
c)	_______	________
d)	_______	________

3. **EXPERIENCE WITH PROTECTION SYSTEMS:** whether you are a utility engineer or not, if you have experience with the performance of protection systems, please answer the following questions.

Please rate your satisfaction with the functional performance of the different relaying systems that you are familiar with or are using. **Do not consider the quality of specific manufacturer's relays in this question but only functional performance.**

Transmission Line Protective Relaying Functions:

1. Distance Relays for Multiphase Faults

No experience		☐	
Needs improvement	☐yes		☐no
Digital Relays	☐yes		☐no

2. (Earth) Ground Distance

No experience		☐	
Needs improvement	☐yes		☐no
Digital Relays	☐yes		☐no

3. (Earth fault) Overcurrent
Ground Relays: Inverse or Definite IDMTL/DTL

No experience		☐	
Needs improvement	☐yes		☐no
Digital Relays	☐yes		☐no

4. Pilot Relays (Teleprotection)

a) Directional Comparison Blocking
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

b) Unblocking
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

c) Permissive Overreaching Transfer Trip
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

d) Permissive Underreaching Transfer Trip
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

e) Direct Underreaching Transfer Trip
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

f) Acceleration scheme
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

g) Phase Comparison

1) Segregated
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

2) Non-Segregated
- No experience ☐
- Needs improvement ☐yes ☐no
- Digital Relays ☐yes ☐no

i) Current Differential (segregated)
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

j) Current Differential (non-segregated)
(Pilot Wire Relays)
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

k) Current Differential (segregated)
(Pilot Wire Relays)
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

l) Other (Please specify)
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

5. Single Phase Tripping and Reclosing Relays

a) High Speed
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

b) Time Delay
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

6. Multiphase Tripping and Reclosing Relays
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

7. Out-of-Step Detection
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

8. Other (Please specify)
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

Transformer Protective Relaying Functions:

1. Differential Relays Without Harmonic Restraint
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

2. (Sudden Pressure) Buchholz Relays
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

3. Volts-per-Hertz Relays
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

4. Overcurrent Relays
a) Primary Relays
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no
b) Backup to Differential
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no
c) Tertiary Protection
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no
d) Neutral Protection (Restrictive Earth Fault)
No experience ☐
Needs improvement ☐yes ☐no

Digital Relays ☐yes ☐no

6. Distance Relay
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

7. Other (please specify)
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

Bus and Breaker Protective Relaying Functions

1. High Impedance Differential Relays
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

2. Differential with Linear Couplers
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

3. Current Differential Relays
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

4. Pole Disagreement Relays
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

5. Breaker Flashover
   No experience ☐
   Needs improvement ☐yes ☐no
   Digital Relays ☐yes ☐no

6. Breaker Failure Protection
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

Generator Protective Relaying Function

1. Stator Differential
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

2. Stator Ground
No experience ☐
Needs improvement ☐yes ☐ no
Digital Relays ☐yes ☐no

3. Impedance
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

4. Overcurrent Relays
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

5. Maximum Voltage
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

6. Minimum and Maximum Frequency
No experience ☐
Needs improvement ☐yes ☐no
Digital Relays ☐yes ☐no

7.	Loss of Field			
	No experience		☐	
	Needs improvement	☐yes		☐no
	Digital Relays	☐yes		☐no
8.	Out-of-Step			
	No experience		☐	
	Needs improvement	☐yes		☐no
	Digital Relays	☐yes		☐no
9.	Fast Valving			
	No experience		☐	
	Needs improvement	☐yes		☐no
	Digital Relays	☐yes		☐no
10.	Inadvertent Energization			
	No experience		☐	
	Needs improvement	☐yes		☐no
	Digital Relays	☐yes		☐no

ADAPTIVE PROTECTIONS SURVEY

Part 2

Adaptive Protections Possibilities

WHAT IS ADAPTIVE PROTECTION

The Working Group uses this definition of Adaptive protection: *"Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions".*

This concept of adaptive protection usually implies that external information, not normally accessible to the protection system, will be communicated to it. However, some adaptive features can be derived from pre-existing information within a relay, and such instances are also acceptable to the Working Group as valid adaptive protections.

In your opinion, on a scale of 1 to 7 (with 7 being very valuable and 1 being not needed), how valuable is it or would it be to have relays adapt to the following situations. Note that the question has two parts: part (a) and a part (b). In part (b), please indicate if in your view the adaptive feature is available or not available to you in commercially available relays and if you are using the feature. If so, would you please indicate the type of relay which provides the feature.

1a) Operating Time as a Function of the Distance to Fault (settable or not)

A distance relay having this feature determines, before making a trip decision, how far inside the zone the fault appears. If it seems to be near the boundary, the relay integrates fault values for enough time to overcome noise and locate the fault more precisely. If the fault appears well inside, the relay can operate faster without danger of overreaching. Such a relay is sometimes described as having an inverse time-distance characteristic. The mathematical curve describing the fault location and trip time may arise implicitly in the design. In some relays, the user can choose from a family of curves depending on whether trip speed or reach accuracy is more important. ***The adaptive feature is to automatically select a time-current characteristic which gives the best combination of speed, security and dependability depending on the fault location and system state, i.e., normal, alert, emergency or restorative.***

b)

Desirable						Undesirable
7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

2a) Mutual Coupling Compensation in Ground Impedance Protection

Mutual coupling due to transmission lines on the same tower or paralleled along the same right-of-way produces a distance measurement error in ground impedance relays. This error is a function of the system configuration and the resulting zero sequence mutual impedance. Conventional techniques can compensate only if the ground current from the coupled line is available in the same station. An adaptive scheme that knows the system impedance matrix can precalculate the effect on the relaying assuming, for example, a fault at the end of the zone 1 reach, even if the coupled line doesn't terminate in the same station. The impedance matrix would reflect the changed effect occurring when the coupled line is taken out of service and grounded. ***Adaptive protection can compensate the ground impedance measurement by calculating the effect of the mutually coupled line.***

b)

Desirable						Undesirable
7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

3a) High Source Impedance Ratio (SIR) Changing

A high ratio of positive sequence source impedance to positive sequence line impedance (SIR) results in a low voltage and current and, more importantly, a small change in voltage for a fault at either end of a line. Unusually large changes in the SIR which might accompany a wide-area disturbance, can result in voltages that are below the range of the relay. ***An adaptive relay, for example, can be made to adapt its voltage and current sensitivity to accommodate such excursions.***

b)

Desirable						Undesirable
7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

4a) Remote-End Open-Breaker Detection for High-Speed Sequential Tripping

Reliably sense the opening of the far end, for far-end faults on the protected line, to achieve instantaneous sequential clearing for those applications where conventional instantaneous overcurrent units will not provide this response. This will provide fast clearing backup of a conventional pilot relaying system, possibly obviating the need for two pilot systems. Only information available within the substation would be used at the instant of the fault. Information about the external system would be transmitted to the substation prior to the disturbance. This information would allow the identification of distinctive current change patterns at the time of far-end opening, measuring current in various lines within the substation. ***The adaptive feature is the ability to respond to changing external system conditions.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

5a) Load Flow Compensation

Pre-fault load current influences several relay settings and in general makes a relay less sensitive. Using fault detectors, it would be possible to compensate for the pre-fault load data and to improve the sensitivity of overcurrent, differential, or impedance relays. The latter could be made significantly less sensitive to the effect of fault resistance. ***The adaptive feature is the improvement in relay sensitivity by eliminating the effects of pre-fault load flow on fault-related measurements.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

6a) Fault Type (multiphase vs. single phase) Changing Speed of Operation

Using only normal relaying input signals, the relay would trip multiphase faults more quickly than single phase faults. The benefits would be in terms of improved security and dependability of the protection system. ***The adaptive feature is faster clearing of multiphase faults.***

b)

Desirable						Undesirable
7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

7a) Multi-Terminal Distance Relay Coverage

Zone 1 reach can be increased and Zone 2 overreach can be reduced by inputting the approximate current infeed ratios. These ratios can be precalculated and changed only when the condition of the remote breakers (open vs closed) are changed, or the ratios could be changed based on rough impedance calculations made by the substation computer based on information about system changes. ***The adaptive feature is improved multi-terminal protection in response to external system information.***

b)

Desirable						Undesirable
7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

8a) Variable Breaker Failure Timing

Measurements of system quantities (for example, positive sequence voltage) during a fault indicates the severity of the fault (the lower the voltage the more severe the fault). By increasing the breaker failure timing for the less severe faults, system security will be increased. The particular time vs. positive-sequence voltage characteristic could be preset or could vary with conditions external to the substation based on input from a central computer. ***The adaptive feature is a reduction in back-up breaker tripping based on measurement of system quantities during the fault.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

9a) Permissive Reclosing

Reclosing time can be controlled to maximize success and minimize the delay by initiating the reclose after extinguishing the secondary arc. Until this arc is extinguished, the voltage to ground on the faulted phase(s) will be depressed. When the arc goes out, the voltage will suddenly increase because of the coupling to adjacent phases of the protected line and to parallel lines. With three phase tripping, the sound phases of the protected line are left with a trapped charge or are experiencing oscillations with line-side shunt reactors. This energy will cause a "jump" in the faulted phase voltage once the secondary arc is extinguished. With single phase tripping the sound phase conductors remain energized by the system. ***The adaptive feature is that by measuring line side voltages, reclose time can be controlled to maximize success and minimize delay.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

10a) Adaptive Reclosing

If the poles of a reclosing circuit breaker could be individually controlled, it would be possible to close one pole first, and then after examining the coupled voltages on the un-energized phases, determine if a fault remains on the transmission line. The first pole to be closed could be selected on the basis of having the least likelihood of having a fault. The voltages on the three phases, with only one phase energized, can be used to detect phase-to-phase faults involving either the energized phase and one of the un-energized phases (the two voltages are equal), or both the un-energized phases (again these two voltages are equal, although smaller than when one of the faulted phases is energized). This procedure would minimize the possibility of ever reclosing all three poles into a multi-phase fault. ***The adaptive feature is the elimination of reclosing into a multi-phase fault by controlled individual pole reclosing.***

b)

Desirable / Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

11a) Sympathy Trip Response

High-speed reclosing is a very effective means of responding to sympathy trips (incorrect tripping during a fault). Some users will reclose following a bus differential trip, but not for a transformer differential operation. Also, some users will not high-speed reclose on a transmission line near a power plant because of shaft-fatigue considerations. For applications where high-speed reclosing is not conventionally implemented, such reclosing could be utilized when the computer system detects that the trip was sympathetic. These trips could, for example, be detected by noting the appearance of near normal voltage on the protected circuit immediately after breaker clearing if one end stays closed or by the detection of power flow out of the circuit for a supposedly internal fault. The high-speed reclose could be contingent upon power system conditions; for example, additional shaft fatiguing would be tolerated only when system conditions are critical. ***The adaptive feature is that the reclosing strategy would be adaptable to system conditions.***

b)

Desirable / Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

12a) Adaptive Synchronism Check Angle for Reclosing

The synchronism check angle for reclosing a circuit breaker is generally selected to: i) control the inrush current and synchronizing torque for cases involving generation, and ii) control closing current in a circuit breaker to limit breaker wear and power system transients when reconnecting segments of a power system where an angular difference exists. In either case, the application engineer will preselect the synch check angle to provide reasonable margin to avoid generator or breaker wear or damage. In the event of a system-wide disturbance, with the danger of system collapse, it should be possible to increase the synch check angle by means of secure, remote communication. The predetermined change (or calculated required change) would increase the probability of reclosing one or more key transmission lines to enhance the chances of system survival. The amount of temporary increase in synch check angle at any location would be such that equipment capability is not exceeded (generator, breaker) but the margin is reduced, resulting in the possibility of limited but acceptable higher duty for the infrequent incident. ***The adaptive feature is that by temporarily changing the synchronism check angle for reclosing in the event of a severe system disturbance, the possibility of system survival is increased.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

13a) Proactive Load Shedding

A major disturbance in an integrated power system can cause cascading which can result in the formation of islands due to the imbalance between generation and load. In existing power systems "reactive" load shedding relays are employed to trip pre-selected, fixed loads to balance load generation mismatch during a disturbance. Since the load shedding relays are reacting to the event, large amounts of load can be tripped for major disturbances. However, if a "proactive" load shedding scheme is employed on a system basis, the total amount of load shed during an event may be reduced by the faster acting scheme. This type of scheme would use a centrally located computer to compare the current system conditions with study scenarios to decide the best course of action to avoid or reduce the impact of the disturbance. ***The adaptive feature is the proactive function of recognizing the symptoms of a disturbance and applying the proper load shedding.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

Transformer Protective Relaying Functions

14a) Adaptive Transformer Differential Protection

The slope and the sensitivity of the restraint characteristic must accommodate dissimilar ct accuracy classification and performance due to different primary voltage levels, mismatch of current ratios due to the use of standard cts and fixed relay taps, and power transformer ratio changes due to tap changers, both fixed and Tap Changing Under Load. Large slopes make the relay insensitive to partial winding faults. An adaptive transformer differential relay could reduce the slope by "learning" the ct mismatch and responding to measurements of the tap positions. ***The adaptive feature is the improvement in sensitivity by learning the ct mismatch and using measurements of the tap positions.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

15a) Voltage Change Supervision of Differential Unit

Inrush currents appear in response to step changes in the applied voltage of the transformer and in response to energization of a transformer parallel to the one protected. Thus, if a large differential current appears suddenly without any preceding change in voltage, this would be an indication of an internal fault and allow for fast tripping of the breakers. This function would be disabled after about the first half cycle of the fault before dc saturation of the cts can cause incorrect operation during an external fault. ***The adaptive feature is faster tripping on large differential currents not preceded by a voltage change.***

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

Bus Protective Relaying Functions

16a) Bus Protection Restraint for Arrester Applications.

Bus protection applied to systems with lightning arresters connected to the bus can be affected by arrester operations and must be slowed down or made less sensitive to avoid false operation. The arrester current can be used to temporarily restrain the operation of the relay to permit fast operation of the relay for bus faults. Alternately, voltage supervision might be feasible to use for high speed operating elements of the bus protection because there is some bus voltage even when the arrester operates. Protection for the case when the lightning arrester fails will be provided but may be somewhat slowed down for these cases. The adaptive feature is to use the arrester current to provide faster response of the bus protection.

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

17a) Adaptive Protection and Control

A number of adaptive protection functions have similarities with control functions. Two examples of such functions are:

a)A load and generation dropping or restoring function based upon tie-line flows, system frequency, and real-time estimates of load-generation imbalances.

b)On-load tap changers which could be blocked on command from a central computer in the event of imminent voltage collapse or instability.

The adaptive feature in such systems is the use of central computer system commands to supervise the performance of protection and control systems. In your view, are such systems now available, or are they desirable? If you have any suggestions for adaptive features of this kind, please indicate them in items (18) and (19) below.

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

18a) ....

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

19a) ....

b)

Desirable Undesirable

7	6	5	4	3	2	1

☐ Not Available ☐ Available ☐ Using

Relay Type ________

APPENDIX II

Suggestions of Adaptive Features by Japanese Responders

(18) Real time prediction type stabilizing protection[3,17,18,20]

This protection predicts power system instability with real-time calculations (mainly post-fault) using power, voltage, currents and/or voltage phase difference between remote locations, and initiates load shedding, generator shedding and/or power system separation, when danger is detected by the calculation.

Usually the real-time data from remote locations are transmitted via telecommunication links. In some cases, however, some stabilizing protection using only local data within a substation for the real-time data is applied.

(19) Lost power compensation type stabilizing protection[3,4]

Operation of this protection depends on loss of power transmitted before disturbances. Values of power transmitted at principal points of the power transmission network are kept in memory during normal operation. When power system islanding occurs because of disturbances, load shedding or generator shedding is initiated depending on lost power (sometimes negative) of the islanded system.

The lost power is calculated with information of switchgear states and of predisturbance power. Although numerical information for calculating shedding power would be transmitted prior to the disturbance, only an on-off signal would be transmitted at the instant of disturbance.

Basically, shedding power is approximately equal to the lost power of the islanded system. However the following options can be applied:

- Shedding power is decreased from the lost power depending on the generating capacity of the islanded system.
- Shedding power is corrected with dropped load which is estimated depending on the voltage drop during fault.
- Shunt capacitors, shunt reactors and/or cable liens are switched depending on loss of reactive power.
- Most of calculated shedding power is shed in the first stage of load shedding. If voltage and/or frequency does not recover, the remaining power is shed in the second stage.

(20) On-line stability calculation type stabilizing protection[21,22]

This protection operates according to results of the on-line stability calculation. It continuously collects information of power system conditions and repeats stability calculations about various expected severe disturbances on the prevailing condition.

Appropriate remedy actions (load shedding, etc.) to reduce the impact of the disturbances respectively should be chosen with additional stability calculations for the various expected disturbances that are judged to be unstable in the former stability calculations.

When one of the disturbances for which the actions have been chosen occurs, the action for the disturbance should be performed immediately.

(21) Change of Mutual Coupling Compensation depending on Comparison of zero sequence currents between the protected line and the parallel line

Ground distance relays, which perform the mutual coupling compensation only when the magnitude of the zero sequence currents of parallel lines are less by a certain amount compared with that of the protected line.

This adaptive feature is a countermeasure to erroneous overreaching[5] of the healthy line ground distance relays equipped with mutual compensation, when faults occur on the parallel line.

(22) Adaptive converting of protection schemes in cases of protection system failures which lose partial functions.

For example, with "n" terminal differential protection, if one terminal data are lost due to protection system failures (including telecommunication failures), the protection is converted into distance protection or overcurrent protection using "n-1" terminal data.

This feature minimizes deterioration of the protection capability under some protection system failure circumstances.

(23) Fault locating error estimation of distance relay type transmission line fault locator.

On the distance relay type transmission fault locator, locating errors are estimated and the location data are registered with the form of (xx±yy) km where xx is the estimate, and yy is the uncertainty associated with the estimate.

The distance relay type fault locator locates faults by using voltage drop of the faulty transmission line. Locating errors arise dependent on fault voltage, faulty branch voltage drop and healthy branch voltage drop (in case of multi-terminal lines).

The locating errors are estimated with these fault voltage and voltage drops.

(24) Voltage change supervision of harmonic restraint.

During faults on power systems adjoining HVDC systems, TCSC bypasses or large power cable network, there is a possibility that protection with harmonic restraint, such as transformer differential protection or zero sequence overcurrent protection taking measures for magnetic storm, may fail to trip due to distorted fault currents having rather lower high frequency components such as second harmonic.

Step drops appearing in the applied voltage of the protection section can be used in order to block the harmonic restraint of the protection.

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