AN ADAPTIVE RELAYING APPROACH TO DISTRIBUTION SYSTEM PROTECTION

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INTRODUCTION

The present practice for setting relays consists of analyzing critical operating conditions of the power system and determining settings that would ensure proper coordination for primary and backup protection. Two major difficulties are, however, encountered, firstly identifying all operating conditions of concern in advance and secondly determining a set of relay settings that would be optimum for all normal and abnormal operating conditions. Often, the results are not ideal; some relays continue to 'sympathy trip' because of inadequate selectivity. Other undesirable aspects include longer relay operating times and non-operation for certain conditions. Several attempts have been made in the past to alleviate such problems but only partial success has been achieved. The bottle neck has been the type of technology used to design and manufacture relays.

With advancements in digital technology and the development of microprocessor-based relays [1], collecting information, handling complex logic, and the ability for a relay to communicate with other relays and control devices has become relatively easy. These relays make it possible to continuously monitor the state of a power system, analyze it in real-time, and change the relay settings to those most appropriate at that time. This approach, classified as adaptive relaying, has been used by the authors for designing a protection system for the distribution network of the 'City of Saskatoon'.

In recent years, adaptive relaying concepts have been proposed [1-6]. The Adaptive Protection and Control Working Group of the IEEE Power System Relaying Committee recently conducted a survey [7] which reveals that while protection engineers are satisfied with presently used systems, they consider it desirable to take advantage of the improvements that can be achieved by using adaptive relaying concepts.

This paper outlines the design of an adaptive relaying system for a distribution network [8]. The developed software and hardware are described. The scheme, implemented in the Power System Research Laboratory at the University of Saskatchewan, is briefly outlined. The paper also examines the consequences of partial and total failure of communication between relays and the station computers, and the station computers and the central computer. Measures to alleviate such situations are discussed. Results, obtained from system studies conducted in the laboratory, are presented.

THE ADAPTIVE RELAYING SYSTEM

Figure 1 shows the functional block diagram of the adaptive relaying system designed for a distribution substation of the 'City of Saskatoon'. Only relays and their controllers are shown for the sake of clarity. Similar configurations of relays and computers are used at other substations. The relays sample bus voltages and line currents via voltage and current transformers, auxiliary transformers, analog to digital converters and multiplexers. Each relay processes quantized samples and calculates voltage and current phasors. During normal operating conditions, each relay provides the phasor measurements to the station control computer at regular intervals. The relays also check the status of local isolators and circuit breakers and provide the information to the station computers. In addition to communicating with the relays, the station computers pass on the collected information to the central computer at pre-specified intervals, say one hour.

The central computer estimates the system state and decides whether the relay settings should be changed or not. If it decides to change the settings, it calculates them and conveys them to the relays via the station control computers. The relays implement the new settings and send confirmation messages to the central computer via the station computers. If the central computer decides not to change the settings, the decision is communicated to the relays for sharing information and confirming that communication facilities are working properly.

The selected relays and the hardware should be appropriate for the application. Before describing the software and the hardware designed for this application, the distribution system of the 'City of Saskatoon' and the instrumentation used to protect it are briefly described.

THE DISTRIBUTION SYSTEM & INSTRUMENTATION

The Distribution System

The 'City of Saskatoon' distribution network, for which an adaptive relaying system has been designed, is shown in Figure 2. The distribution system consists of five switching stations, Avenue C, Taylor, Friebel, Cowley, and Pleasant Hill substations. Two 138 kV lines, QE-1A and QE-2A, connect the QE generating station of the Saskatchewan Power Corporation to the Ave C substation. Three transformers, provided at the Ave C substation, step down the voltage to 14.4 kV. A 72 kV line, QE-5, connects the QE station to the Pleasant Hill substation, and another 72 kV line, QE-18, connects the QE station to the Cowley, Friebel and Taylor substations.

The substations have 72 kV/14.4 kV step down transformers which are connected to 14.4 kV buses. These buses are interconnected by lines to form the distribution network. Each line connects two substations and is equipped with a circuit breaker at each end. Each breaker is equipped with an overcurrent or a directional overcurrent relay. Non-directional relays are used for protecting 138/14.4 kV and 72/14.4 kV transformers, and load circuits emanating from the substations. All relays are equipped with instantaneous overcurrent elements.

The present operating practice of the 'City of Saskatoon' is to operate each line as a radial circuit while each substation serves its local loads. In the event of loss of power at a substation, lines emanating from it are connected to other substations to restore power to the customers. But for the studies reported in this paper, all 14.4 kV circuit breakers are considered to be closed.

Instrumentation

To select proper instruments for protection and control of the distribution system, information on system parameters and loads, summarized in Table - A, was collected from the Electrical Department of the 'City of Saskatoon'. Load flows for several operating conditions were conducted and relay currents for faults at different locations in the system were calculated. It was noticed that at the peak load time, primary current in the line protected by relay 1-1 is 46.8 kA if a fault occurs on the line-side of the relay. But the current for a fault at the far-end of the line is only 4.9 kA. During minimum load and generation period, the near and far-end fault currents are 42.5 and 4.4 kA respectively. The normal line currents at this location are 398 A at peak load and 181 A at minimum load times. Since, the ratios of the fault current to load current is very high, two sets of cts were selected for each relay location [9], one set for instrumentation and overload protection and the other set for protection during faults. Cts of 1000/5 A ratio were selected for use with overcurrent and directional overcurrent relays at locations that experience fault currents between 10 and 20 kA. For locations experiencing fault currents from 20 to 50 kA, 2000/5 A cts were selected. Cts for metering and overload protection were selected on the basis of maximum load current in the circuit. Cts of 800/5 A ratio were chosen for location 1-1.

It was decided to use separate twelve-bit, A/D converters for instrumentation and overload protection, and phase faults protection. These A/D converters connected to cts via auxiliary transformers and multiplexers provide resolutions of 22.8 A primary current for fault protection and 0.78 A primary current for instrumentation and overload protection.

Figure 3 shows the arrangements of cts and A/D converters used with relay 1-1. While both input channels remain active at all times, the relay processes only one set of data depending on the levels of the inputs.

SOFTWARE

The purpose of adaptive relaying is to change relay settings as load currents and/or expected fault currents change, and/or when the system topology changes. Another desirable objective would be to keep the minimum time delays of all relays close to a selected low value while maintaining proper co-ordination margins. To implement the adaptive relaying scheme, three major software packages were developed, one each for modelling relay characteristics, coordinating relays, and facilitating communication between relays and computers.

Relaying Software

The software, that resides in the non-volatile memory of each directional overcurrent relay, is usually required to perform four tasks, modelling relay characteristics, determining direction of a fault, estimating line currents and voltages, and formulating the trip decision. To develop the software for accomplishing these tasks, the software presently used in overcurrent relays was modified and implemented on a TMS 320C25 DSP microprocessor. Floating point arithmetic was used for computations. Essential features of the four software segments are outlined briefly in this section.

I. Time-current characteristics

The modelling of overcurrent relays can either be based on exponential or polynomial equations [10]. In this application, the equation suggested by the International Electro-technical Commission (IEC) was implemented [11]. This equation provides inverse, very inverse or extremely inverse characteristics depending on the values assigned to its parameters.

Initially, the very inverse characteristic was selected for the relays used in this project. Only one characteristic corresponding to TMS of 1 and currents up to 25 times the pickup value are stored in the processor. Relay characteristics for other values of TMS are calculated in the on-line mode when it becomes necessary to use them.

Since the ratio of currents for the near- and far-end faults is large, instantaneous overcurrent elements were included in the relay design. This ensures high speed clearing of heavy faults and reduces overall tripping times. In addition to the settings of the fault protection relays, the settings of the instantaneous units are changed as the system operating conditions change.

II. Directionality

All line relays in the network are of the directional overcurrent type. Directional features were, therefore, incorporated in them. Using the concept used in electromechanical relays, directionality was implemented by the following equation.

$$T = [(V_r I_r + V_i I_i)(k_1 \cos\tau) + (V_r I_i - V_i I_r)(k_1 \sin\tau)] - k_2 \quad (1)$$

To develop substantial torques during faults, 90° connection angle and maximum torque angles of 30° or 45° can be used. The developed software allows the user to select these angles at the time of commissioning the relays. Also, $\cos\tau$ and $\sin\tau$ are calculated at the time of commissioning the relays and are stored in the microprocessor memory. Memory action is incorporated to ensure proper operation during three phase faults when polarizing voltages collapse.

III. Estimating currents and voltages

Currents and voltages usually contain components of fundamental and other frequencies, and exponentially decaying dc. High frequency components are suppressed by analog and digital filters. In this project, Least Error Square (LES) filters [12] were used to estimate the real and imaginary components of voltage and current phasors. The waveform of each input was assumed to be made up of an exponentially decaying dc, and fundamental, second, third, fourth and fifth harmonics. Sampling rate of 720 Hz and data window of 13 samples were selected.

IV. Trip decision logic

This segment of the software uses the estimates of currents and voltages, and the torque calculated by the directional units and decides whether a relay should issue a trip command or not. The directional elements checks if the torque is positive or not. If torque is positive the software checks the magnitude of the current phasor. If it is larger than the threshold of the instantaneous unit, a trip command is issued after a small delay. Processing of data received during the delay continues to ensure that the fault is not of a transient nature. If the current is less than the setting of the instantaneous unit but larger than the pickup value of the fault relays, a trip command is issued after an appropriate time delay which is determined by the relay characteristic. The directionality and magnitude of the current phasor are checked every time a new set of samples are received.

The time delay emulates the selected time-current characteristic. Since the current can change with time, the software integrates a function that depends on the observed current [13].

During implementation, a look-up table is prepared and stored in the relay memory. The table contains weighting factors corresponding to current multiples from 1 to 25 and TMS equals to 1. Other values of TMS are implemented by selecting appropriate target numbers rather than by changing the look-up table.

Coordination Software

An adaptive relaying system must recognize, in real-time, changes in the system operating state and adjust relay settings accordingly. To perform these functions, four software modules, one each for detecting topology of the system, estimating the system state, calculating fault currents and determining the relay settings, were developed. The softwares were written in FORTRAN, and were compiled with Microsoft FORTRAN for use in personal computers. These software modules are briefly described in this section.

I. Network topology detection

In the distribution system, each line is controlled by dedicated circuit breakers. As such, the status of breakers and isolators adjoining them were used for identifying the system topology. The following procedure was used.

1. A data table, containing the identification of each line and the circuit breaker and isolators controlling it, is prepared. the parameters of the lines are also included in this table.
2. Another table which contains information concerning the real-time status of circuit breakers and isolators is prepared. The status of a closed circuit breaker/isolator is designated by '1' and the status of an open circuit breaker is designated by '0'.
3. The third table is then prepared from the first table by extracting only the lines whose controlling circuit breakers and isolators are closed. This table, therefore, contains a list of all lines which are in operation at that time.

II. State estimation

Currents in various branches of the network and voltages at system buses are needed for determining the pickup currents of overload relays and for conducting fault analysis. While several techniques are available in the literature, the fast decoupled technique was used in this application.

III. Fault analysis

A fault analysis program was developed using the Thevnin's equivalent approach. In this method, changes of currents and voltages caused by a short circuit are determined. These changes are superimposed on the pre-fault currents and voltages computed by the state estimation software.

IV. Relay settings

The use of the graph theoretic approach for coordinating directional relays was suggested in the past [14,15]. This approach provides a solution which is the best of the alternative settings considered but does not provide an optimal solution. A parametric optimization approach, proposed recently [16], uses the Simplex method to optimize the time multiplier settings (TMS). Optimal values of the pickup currents for selected values of TMS are then determined using a similar approach.. To estimate the pickup current the generalized reduced gradient technique is used. Only a few constraints, which considered faults at the midpoints of circuits, were included in that work.

In the application reported in this paper, pickup currents were estimated before applying the optimization technique. As a result, the equation, used for modelling the relay characteristics, became linear. The two phase Simplex method was used. It was observed during this work that constraints play a vital role in formulating the optimization problem. A large number of interrelated constraints result from different perturbations in the system. This could lead to situations in which all constraints can not be met. Phase-I of the two-phase Simplex method was, therefore, used to detect the infeasible constraints, which were excluded before starting phase-II.

Operating times of relays, for primary protection during near-end faults, were minimized. The TMS values were the decision variables, and the operating times of back-up relays formed the inequality constrains. A minimum operating time of 0.05 s and a coordination time interval (CTI) of 0.2 s were used in this project.

Communication Software

Communication is a major activity that is used by the relays to exchange information with the station computers, and by the station computers to communicate with relays and with the central control computer. Two application softwares are required for information exchange, one for communication between the relays and the station computers and the other for communication between the central control computer and the station computers. For communication between the relays and the station computers, Local Area Network (LAN) in 'Token ring' configuration is used [14,15]. Serial communication (RS 232) is used for information exchange between the station computers and the central control computer.

I. Communication between relaying processors and station computers

This function is performed by an application software which was developed using a commercially available Record Management Software [19]. The software is in two segments, one segment resides in the station computer and the other in each relaying pc. The software that resides in the station computer manages the records in a table format. The table contains the information concerning the relays, such as, relay designations, pickup currents, TMS settings, bus voltages, line currents and the status of the controlling circuit breakers and isolators. The table is updated on an hourly basis or when the topology changes. The information in the updated table is also provided to the central control computer. The second segment of the software, that resides in each relaying pc, also manages records in a table format but only information pertinent to its relay is stored. This data is also updated on an hourly basis or when the network topology changes.

II. Communication between station computers and the central computer

The development of this software is in progress. For this application, another commercially available asynchronous communication software [20] is being used.

IMPLEMENTATION OF ADAPTIVE RELAYING

While the required software was being developed and the hardware was being acquired for implementing the adaptive relaying system in the laboratory, designs were completed for applying adaptive relaying techniques to the Taylor substation.

An experimental set up was completed in the Power System Research Laboratory at the University of Saskatchewan. The block diagram of the control and relaying scheme is shown in Figure 4. Since the selected substation has five circuits, five relays were implemented on DSP-C25 boards [21]. Each board is placed in a dedicated personal computer.

One pc has been used as a substation controller which also functions as a 'File Server' for the LAN. This pc is connected to the five relaying pc's via a 'Multi Station Access Unit (MAU)' [18]. This unit allows eight pc's to be connected with the LAN. It supports up to 16 Mbps token ring networks over unshielded twisted pair, shielded twisted pair (STP), and fiber optics. In this project, STP cable has been used for connecting the station controller to the relaying pc's via MAU. Another pc has been used as a central control computer. It is equipped with a 'Digiboard' that has eight asynchronous RS 232 ports [22]. At present, only one port connects to the station computer for the Taylor substation. For the RS 232 communication link, a co-axial cable with null modem has been used.

ADAPTIVE SYSTEM FAILURE

It is proposed to monitor the distribution system and modify relay settings at one hour intervals. The central controller will determine the revised relay settings. The procedure will work during normal operating conditions but during failures, such as communication between computers at different hierarchical levels, some remedial measures must be taken. It is proposed that during the total failure of the communication system, relays go into a program mode and fetch settings which will be precalculated and stored in non-volatile memory. However, if communication between a substation control computer and central computer or between a substation controller and its relays fail, it will be treated as a partial failure of the adaptive system. Under this condition relay pickup and time multiplier settings will be updated locally.

Proposed method for setting relays locally

Since a relay continuously monitors the local operating levels of the system it should be possible to change its pickup value locally. It can be shown that the new time multiplier settings calculated by using Equation 2 would be acceptable for use over short durations of time.

$$TMS_2 \approx \frac{I_{pickup1}}{I_{pickup2}} TMS_1 \qquad (2)$$

SYSTEM STUDIES

System studies were carried out in two parts. In the first part, relay settings and relay operating times were determined by using the adaptive approach. In the second part, estimates of the time multiplier settings were calculated assuming that adaptive system is not functioning properly.

I. Normal functioning of adaptive system

To investigate the suitability of the developed system, the following four operating states of the distribution system were considered.

i) Maximum system load and generation with line 1-20 closed (MXLG-1),
ii) Minimum system load and generation with line 1-20 closed (MNLG-1),
iii) Maximum system load and generation with line 1-20 open (MXLG-2) and
iv) Minimum system load and generation with line 1-20 open (MNLG-2).

In each case, the state estimator calculated the pre-fault currents in the lines and voltages at the substation buses. The fault analysis program then calculated currents for faults on each line. The coordination program used this information and calculated the pickup currents for the overload, phase fault and instantaneous overcurrent relays.

The program sets the overload relays at 200% of the line currents during the maximum load condition. As the load decreases pickup settings are reduced but settings are never reduced to values less than the maximum line currents. It also verifies that the settings do not affect the coordination between backup overload relays and primary phase fault relays. The pickup settings of phase fault relays are determined in such a manner that the fault currents are always less than 25 multiples of the pickup currents. They must also be more than the pickup settings of the overload relays. The relay setting program then determines the time multiplier settings that would ensure coordination of all line protection relays. The program also selects instantaneous tap settings.

Table 1 shows the relay settings of the line relays along with load currents and fault currents determined by the developed software. Table 2 through 5 show the primary and backup operating times of the relays.

Figure 5 illustrates a case where by changing the pickup setting of the overload relay, 5-2, it can be made to operate for a far-end fault for which it does not operate when non-adaptive approach is used. During non-adaptive application, pickup setting is not revised while the source impedance changes due to changes of load, generation level and circuit configuration. As a result, relay 5-2 does not pickup a far-end fault on the line between buses 5 and 4. When the adaptive approach is used, pickup current is reduced and therefore, relay 5-2 detects the fault.

Figure 6 shows how selectivity suffers when the non-adaptive approach is used. Pickup settings are selected on the basis of maximum load and generation condition to avoid tripping during normal operation. To maintain relay coordination, higher time multiplier settings are chosen. But even with the higher TMS values, selectivity cannot be achieved at all operating conditions. In the case of Figure 6, relay 4-1 does not coordinate with relay 5-1 for a fault at 1-1. The problem is, however, alleviated by the use of the adaptive approach.

Figure 7 and 8 show the relay operating times when adaptive and non-adaptive approaches are used during minimum load and generating conditions. These figures show that the relay operating times are less when the adaptive approach is used.

Figure 9 shows the percent of line protected by the instantaneous relays when adaptive and non-adaptive approaches are used at minimum load and generating conditions. In the non-adaptive approach, instantaneous relay will be selected on the basis of maximum load and generating conditions which results lower line coverage during minimum operating state.

II. During the failure of adaptive system

The procedure proposed for determining the time multiplier settings locally was also checked. The TMS values were computed using equation 2. The results were compared with the settings that adaptive approach would have provided. Figure 10 shows that the locally estimated settings are close to those estimated by the adaptive system. These settings can, therefore, be used during system failures.

CONCLUSIONS

The design of an adaptive relaying system for a distribution network has been described in this paper. The softwares designed for the system have also been described. The hardware aspects and implementation of the adaptive approach have been outlined. The consequences of adaptive system failure and remedial measures have been discussed. Some results from applying the approach to the 'City of Saskatoon' distribution network, have been presented.

The system studies reveal that the use of adaptive protection reduces the relay operating times and improves the selectivity of the protection system. It is shown that by lowering the pickup setting using adaptive approach, the problem of non-operation of a relay has been alleviated. The study also demonstrates that the reach of the instantaneous relays is improved by using the adaptive protection.

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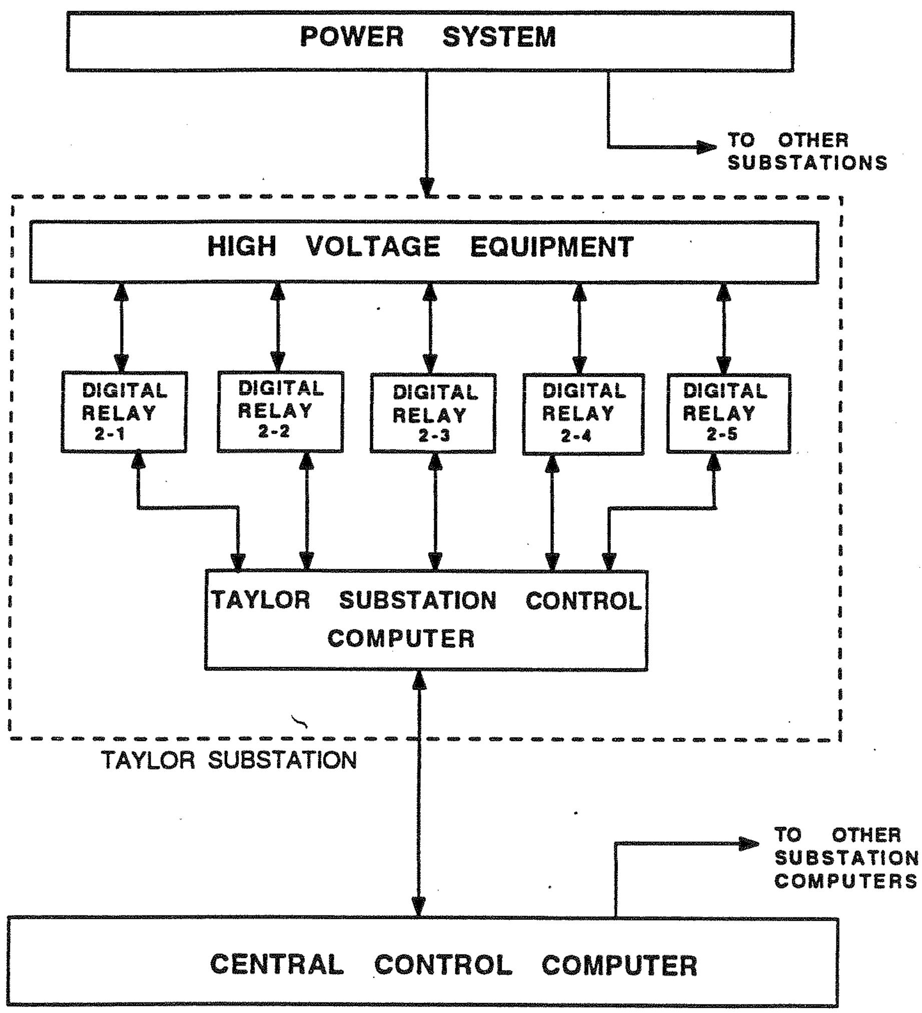

Figure 1 Block diagram of the developed adaptive system for the Taylor substation.

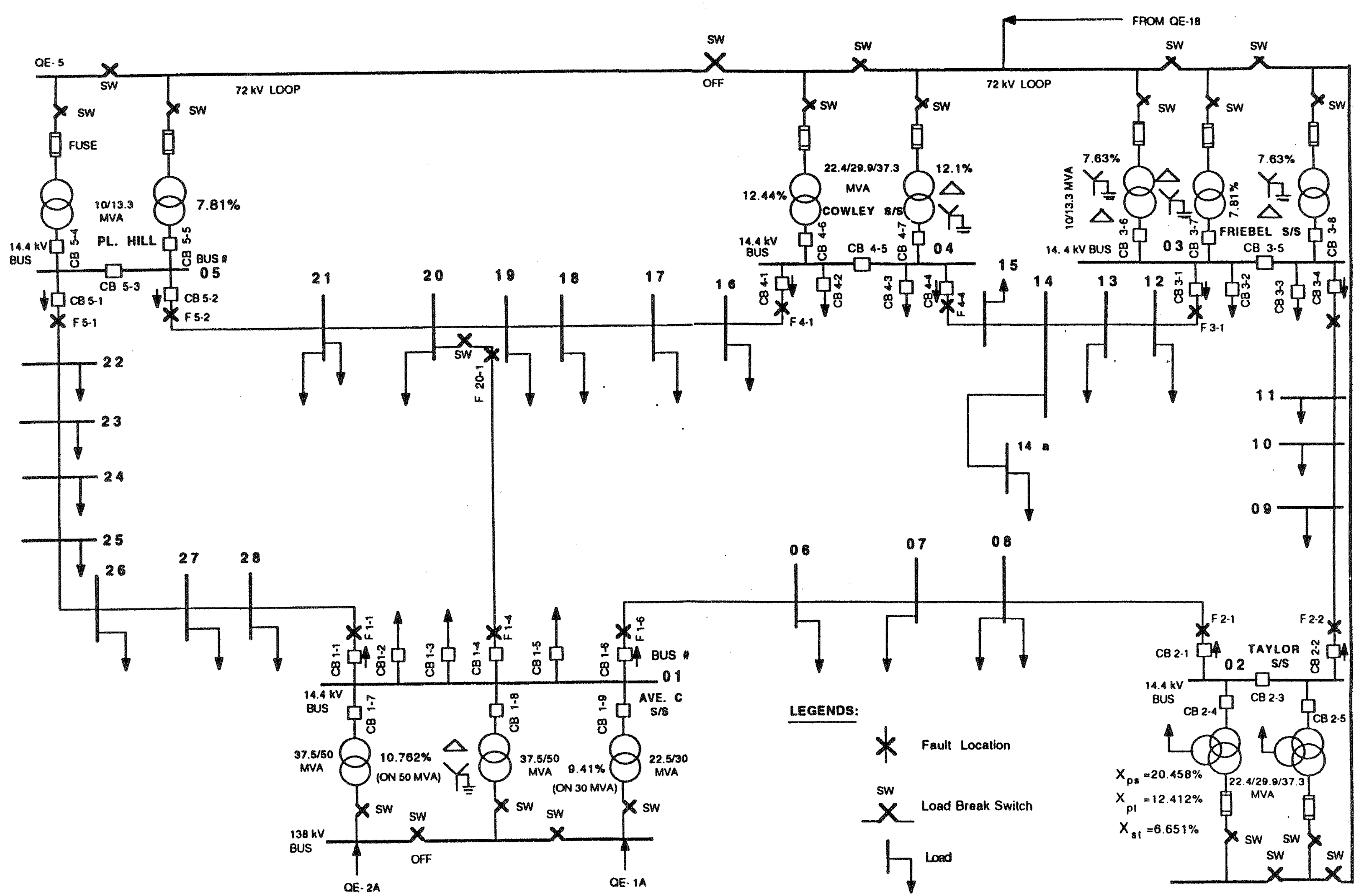

Figure 2 Single line diagram of the distribution system.

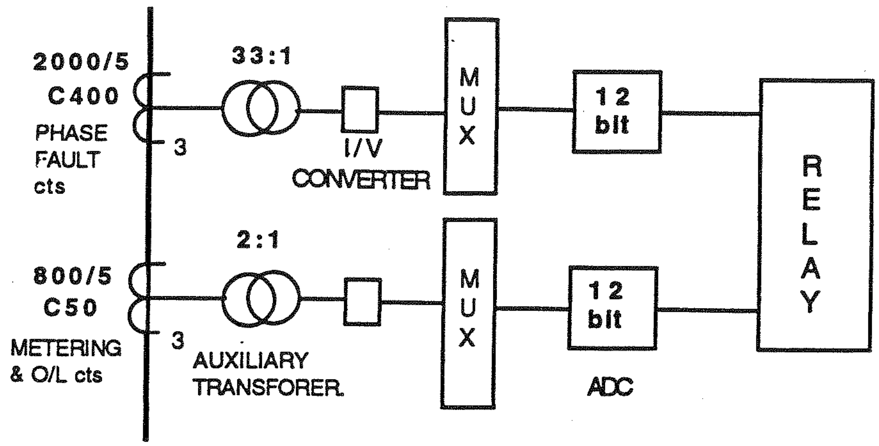

Figure 3 Arrangement of cts and A/D converters for the relay at location 1-1.

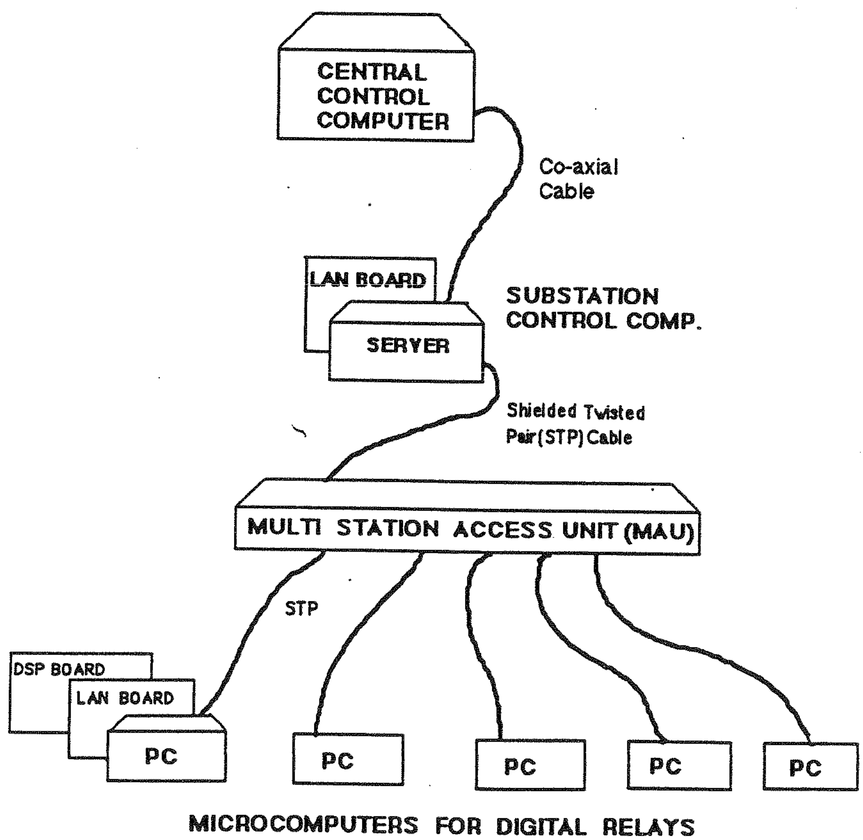

Figure 4 Laboratory arrangement of the adaptive relaying system.

Table 1. Loads, fault currents and settings of the relays.

Relay	Operat. Cond.	Load Curr. (A)	Fault Currents (Amps)		Phase Fault & O/L cts	Secondary Pickup/ Tap Settings			TMS for O/C & O/L
			Near-end Faults	Far-end Faults		O/L Relay	O/C Relay	Inst. Relay	
1 -1	MXLG-1	398	46815	4941	2000/5 & 800/5	7.00	4.75	16.0	0.088
	MNLG-1	181	42546	4440		6.00	4.50	14.5	0.084
	MXLG-2	646	40648	5703		8.00	4.25	18.5	0.085
	MNLG-2	337	36503	5273		7.00	3.75	17.0	0.086
1-4	MXLG-1	404	42642	3875	2000/5 & 600/5	6.75	5.00	13.0	0.084
	MNLG-1	192	38804	3692		6.00	4.50	12.0	0.086
	MXLG-2	-	-	-		-	-	-	-
	MNLG-2	-	-	-		-	-	-	-
1-6	MXLG-1	522	42490	8741	2000/5 & 600/5	9.25	4.50	28.5	0.089
	MNLG-1	223	38940	8670		8.25	4.00	28.0	0.086
	MXLG-2	557	38328	8947		9.25	4.00	29.0	0.088
	MNLG-2	298	34605	8638		8.25	3.50	28.0	0.100
2-1	MXLG-1	241	15331	6738	1000/5 & 400/5	9.00	3.75	44.0	0.148
	MNLG-1	111	13998	6403		6.75	3.75	42.0	0.140
	MXLG-2	362	15246	6764		9.00	3.75	44.0	0.149
	MNLG-2	154	13971	6471		8.00	3.75	42.0	0.141
2-2	MXLG-1	81	18574	4806	1000/5 & 200/5	7.25	3.75	31.0	0.088
	MNLG-1	34	17369	4669		6.25	3.50	30.0	0.088
	MXLG-2	164	18493	4828		8.25	3.75	31.5	0.100
	MNLG-2	78	17278	4693		7.25	3.50	30.5	0.106
3-1	MXLG-1	100	16179	3526	1000/5 & 300/5	6.00	3.25	23.0	0.108
	MNLG-1	48	14784	3407		5.00	3.00	22.0	0.088
	MXLG-2	200	16207	3560		6.75	3.25	23.0	0.089
	MNLG-2	97	14812	3442		6.00	3.00	22.5	0.090
3-4	MXLG-1	210	14915	4544	1000/5 & 300/5	7.00	3.00	29.5	0.147
	MNLG-1	103	13540	4357		6.25	2.75	28.5	0.157
	MXLG-2	113	14887	4577		6.25	3.00	30.0	0.149
	MNLG-2	53	13502	4387		5.25	2.75	28.5	0.159
4-1	MXLG-1	153	14509	1806	1000/5 & 300/5	7.75	3.00	12.0	0.221
	MNLG-1	75	13240	1739		6.50	2.75	11.5	0.267
	MXLG-2	261	14596	3361		8.75	3.00	22.0	0.096
	MNLG-2	123	13299	3180		7.75	2.75	21.0	0.100
4-4	MXLG-1	158	15596	3497	1000/5 & 200/5	8.00	3.25	23.0	0.092
	MNLG-1	76	14360	3375		7.00	3.00	22.0	0.100
	MXLG-2	79	14029	3446		7.00	3.00	22.5	0.100
	MNLG-2	30	12838	3319		6.00	2.75	21.5	0.108
5-1	MXLG-1	389	16499	2725	1000/5 & 400/5	9.75	4.00	18.0	0.073
	MNLG-1	167	15380	2265		8.50	4.00	15.0	0.068
	MXLG-2	326	11941	4395		9.75	4.00	29.0	0.084
	MNLG-2	50	10958	3983		7.50	4.00	26.0	0.076
5-2	MXLG-1	322	13185	1251	1000/5 & 800/5	6.75	6.25	8.0	0.035
	MNLG-1	157	12314	1109		5.75	6.25	7.5	0.033
	MXLG-2	612	14130	3512		7.75	6.25	23.0	0.038
	MNLG-2	298	13171	3212		6.75	6.25	21.0	0.037

Table 2. Operating times of the relays for primary and backup protection during MXLG-1.

Fault Locat.	Relay Location	Primary Protection			Backup Protection		
		Relay	Type of Prot.	Relay Operat. Time (s)	Relay	Type of Prot.	Relay Operat. Time (s)
1-1	Near-end	1-1	Inst.	0.033	2-1 5-2 4-1	O/C O/C O/C	0.250 0.300 0.608
	Far-end	5-1	O/C	0.408	4-1	O/C	0.608
5-1	Near-end	5-1	Inst.	0.033	4-1 1-4	O/C O/C	1.484 0.518
	Far-end	1-1	O/C	0.250	2-1 4-1	O/C O/C	1.251 1.484
1-6	Near-end	1-6	Inst.	0.033	5-1 4-1 5-2	O/C O/C O/C	0.408 0.608 0.300
	Far-end	2-1	O/C	0.250	3-4	O/C	0.944
2-1	Near-end	2-1	Inst.	0.033	3-4	O/C	0.303
	Far-end	1-6	O/C	0.290	5-1 4-1 5-2	O/L O/L -	8.10 12.06 -
2-2	Near-end	2-2	Inst.	0.033	1-6	O/C	0.290
	Far-end	3-4	O/C	0.303	4-4	O/C	2.326
3-4	Near-end	3-4	Inst.	0.033	4-4	O/C	0.290
	Far-end	2-2	O/C	0.220	1-6	O/C	4.701
3-1	Near-end	3-1	Inst.	0.033	2-2	O/C	0.220
	Far-end	4-4	O/C	0.283	5-2 1-4	- -	- -
4-4	Near-end	4-4	Inst.	0.033	5-2 1-4	O/L O/C	2.984 1.210
	Far-end	3-1	O/C	0.329	2-2	O/C	4.601
4-1	Near-end	4-1	Inst.	0.033	3-1	O/C	0.329
	Far-end	5-2 1-4	O/L O/C	2.984 0.8878	1-1 2-1 1-1	- - -	- - -
5-2	Near-end	5-2	Inst.	0.033	1-1	O/C	0.250
	Far-end	4-1 1-4	O/C O/C	1.484 0.416	3-1 2-1 1-1	O/L O/C O/C	17.50 1.251 0.742
1-4	Near-end	1-4	Inst	0.033	5-1 2-1	O/C O/C	0.408 0.250
	Far-end	5-2 4-1	O/C O/C	0.327 0.608	3-1	O/L	3.260

Table 3. Operating times of the relays for primary and backup protection during MNLG-1.

Fault Locat.	Relay Location	Primary Protection			Backup Protection		
		Relay	Type of Prot.	Relay Operat. Time (s)	Relay	Type of Prot.	Relay Operat. Time (s)
1-1	Near-end	1-1	Inst.	0.033	2-1	O/C	0.250
					5-2	O/C	0.327
					4-1	O/C	0.698
	Far-end	5-1	O/C	0.498	4-1	O/C	0.698
5-1	Near-end	5-1	Inst.	0.033	4-1	O/C	1.665
					1-4	O/C	0.490
	Far-end	1-1	O/C	0.772	2-1	O/C	1.255
					4-1	O/C	1.667
1-6	Near-end	1-6	Inst.	0.033	5-1	O/C	0.498
					4-1	O/C	0.698
					5-2	O/C	0.327
	Far-end	2-1	O/C	0.250	3-4	O/C	0.939
2-1	Near-end	2-1	Inst.	0.033	3-4	O/C	0.307
	Far-end	1-6	O/C	0.264	5-1	-	-
					4-1	O/L	11.430
					5-2	-	-
2-2	Near-end	2-2	Inst.	0.033	1-6	O/C	0.264
	Far-end	3-4	O/C	0.307	4-4	O/C	2.161
3-4	Near-end	3-4	Inst.	0.033	4-4	O/C	0.290
	Far-end	2-2	O/C	0.210	1-6	O/C	3.044
3-1	Near-end	3-1	Inst.	0.033	2-2	O/C	0.210
	Far-end	4-4	O/C	0.290	5-2	-	-
					1-4	-	-
4-4	Near-end	4-4	Inst.	0.033	5-2	-	-
					1-4	O/C	1.105
	Far-end	3-1	O/C	0.253	2-2	O/C	3.637
4-1	Near-end	4-1	Inst.	0.033	3-1	O/C	0.253
	Far-end	5-2	O/L	2.168	1-1	-	-
		1-4	O/C	1.105	2-1	-	-
					1-1	-	-
5-2	Near-end	5-2	Inst.	0.033	1-1	O/C	0.772
	Far-end	4-1	O/C	1.665	3-1	O/L	6.364
		1-4	O/C	0.490	2-1	O/C	1.255
					1-1	O/C	1.334
1-4	Near-end	1-4	Inst.	0.033	5-1	O/C	0.498
					2-1	O/C	0.250
	Far-end	5-2	O/C	0.326			
		4-1	O/C	0.698	3-1	O/L	2.050

Table 4. Operating times of the relays for primary and backup protection during MXLG-2.

Fault Locat.	Relay Location	Primary Protection			Backup Protection		
		Relay	Type of Prot.	Relay Operat. Time(s.)	Relay	Type of Prot.	Relay Operat. Time (s)
1-1	Near-end	1-1	Inst.	0.033	2-1	O/C	0.250
	Far-end	5-1	O/C	0.252	4-1	O/C	1.200
5-1	Near-end	5-1	Inst.	0.033	4-1	O/C	0.281
	Far-end	1-1	O/C	0.486	2-1	O/L	5.630
1-6	Near-end	1-6	Inst.	0.033	5-1	O/C	0.252
	Far-end	2-1	O/C	0.250	3-4	O/C	0.881
2-1	Near-end	2-1	Inst.	0.033	3-4	O/C	0.304
	Far-end	1-6	O/C	0.257	5-1	O/C	2.762
2-2	Near-end	2-2	Inst.	0.033	1-6	O/C	0.258
	Far-end	3-4	O/C	0.304	4-4	O/C	1.750
3-4	Near-end	3-4	Inst.	0.033	4-4	O/C	0.285
	Far-end	2-2	O/C	0.250	1-6	O/C	2.091
3-1	Near-end	3-1	Inst.	0.033	2-2	O/C	0.250
	Far-end	4-4	O/C	0.285	5-2		-
4-4	Near-end	4-4	Inst.	0.033	5-2	O/C	0.285
	Far-end	3-1	O/C	0.267	2-2	O/C	3.300
4-1	Near-end	4-1	Inst.	0.033	3-1	O/C	0.267
	Far-end	5-2	O/C	0.285	1-1	O/L	7.095
5-2	Near-end	5-2	Inst.	0.033	1-1	O/C	0.487
	Far-end	4-1	O/C	0.281	3-1	O/L	1.230

Table 5. Operating times of the relays for primary and backup protection during MNLG-2.

Fault Locat.	Relay Location	Primary Protection			Backup Protection		
		Relay	Type of Prot.	Relay Operat. Time(s.)	Relay	Type of Prot.	Relay Operat. Time (s)
1-1	Near-end	1-1	Inst.	0.033	2-1	O/C	0.250
	Far-end	5-1	O/C	0.257	4-1	O/C	1.301
5-1	Near-end	5-1	Inst.	0.033	4-1	O/C	0.280
	Far-end	1-1	O/C	0.484	2-1	O/L	4.810
1-6	Near-end	1-6	Inst.	0.033	5-1	O/C	0.257
	Far-end	2-1	O/C	0.250	3-4	O/C	0.843
2-1	Near-end	2-1	Inst.	0.033	3-4	O/C	0.308
	Far-end	1-6	O/C	0.261	5-1	O/C	2.762
2-2	Near-end	2-2	Inst.	0.033	1-6	O/C	0.261
	Far-end	3-4	O/C	0.308	4-4	O/C	1.614
3-4	Near-end	3-4	Inst.	0.033	4-4	O/C	0.291
	Far-end	2-2	O/C	0.252	1-6	O/C	1.900
3-1	Near-end	3-1	Inst.	0.033	2-2	O/C	0.252
	Far-end	4-4	O/C	0.291	5-2		-
4-4	Near-end	4-4	Inst.	0.033	5-2	O/C	0.304
	Far-end	3-1	O/C	0.258	2-2	O/C	2.824
4-1	Near-end	4-1	Inst.	0.033	3-1	O/C	0.258
	Far-end	5-2	O/C	0.304	1-1	O/L	16.460
5-2	Near-end	5-2	Inst.	0.033	1-1	O/C	0.464
	Far-end	4-1	O/C	0.280	3-1	O/L	1.051

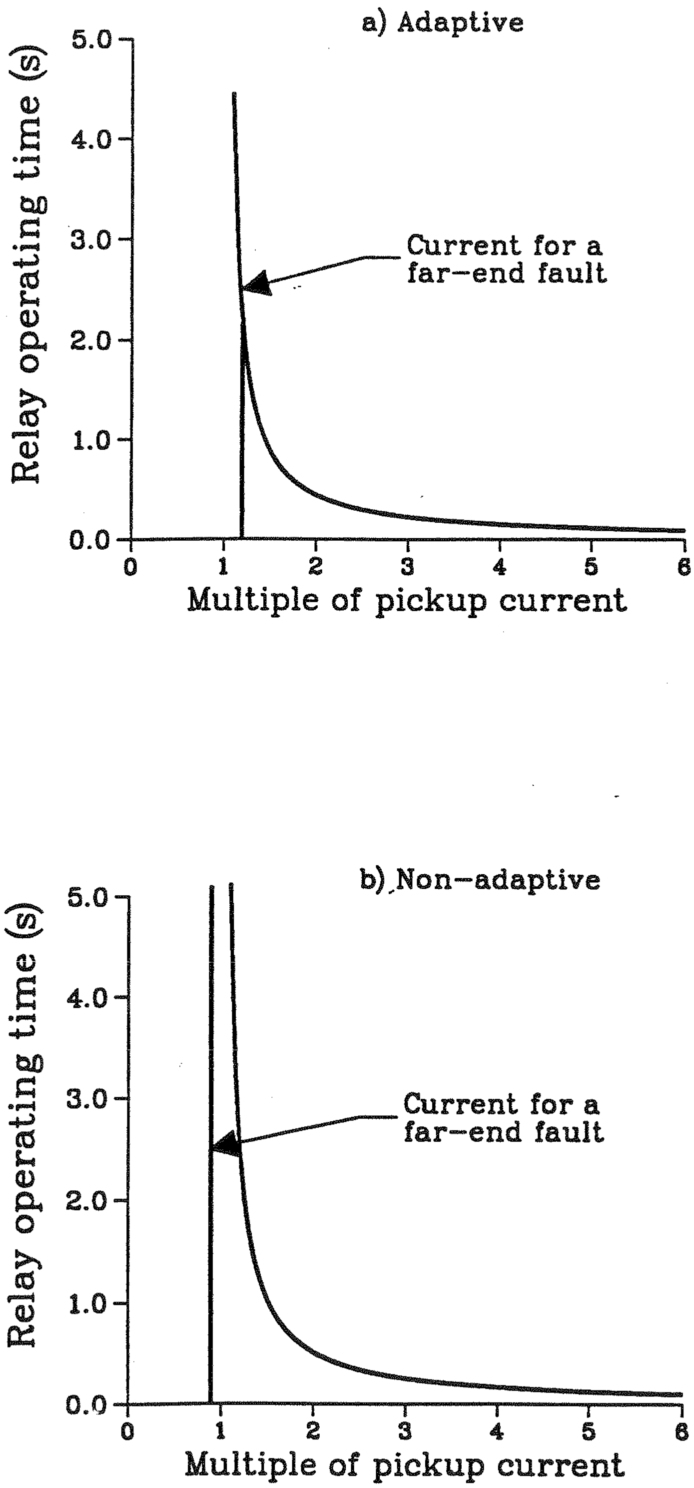

Figure 5 Operating states of relay 5-2 for a far-end fault during condition MNLG-1.

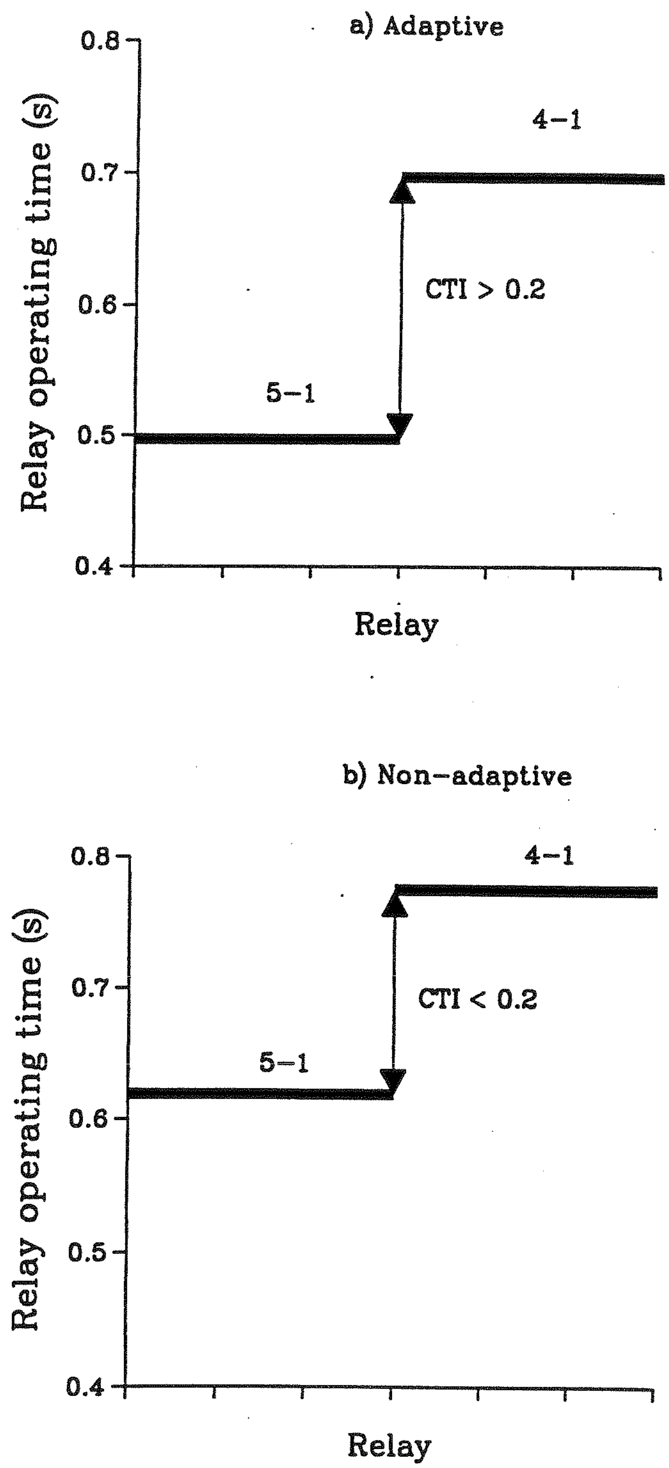

Figure 6 Coordination between relays 5-1 and 4-1 during MNLG-1.

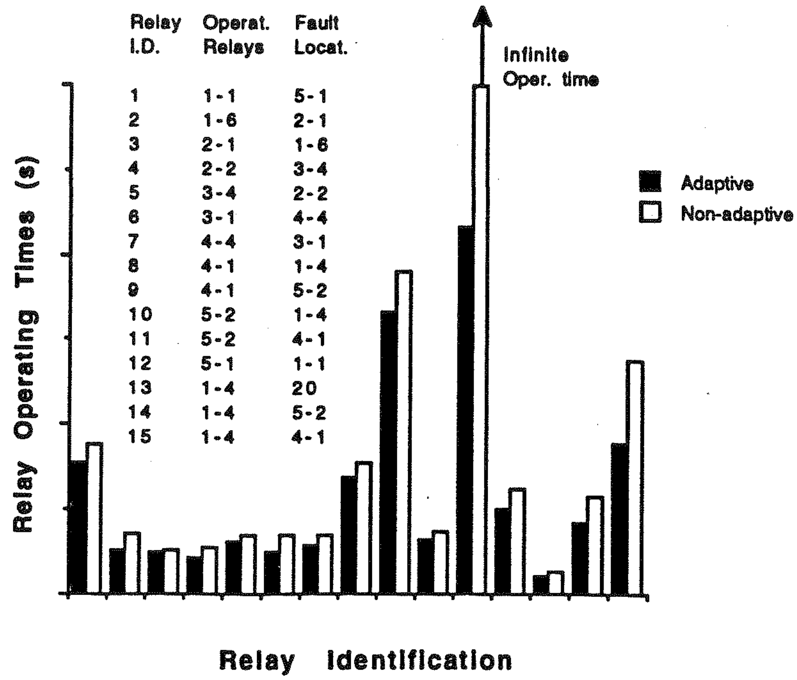

Figure 7 Relay operating times using adaptive and non-adaptive approaches during MNLG-1.

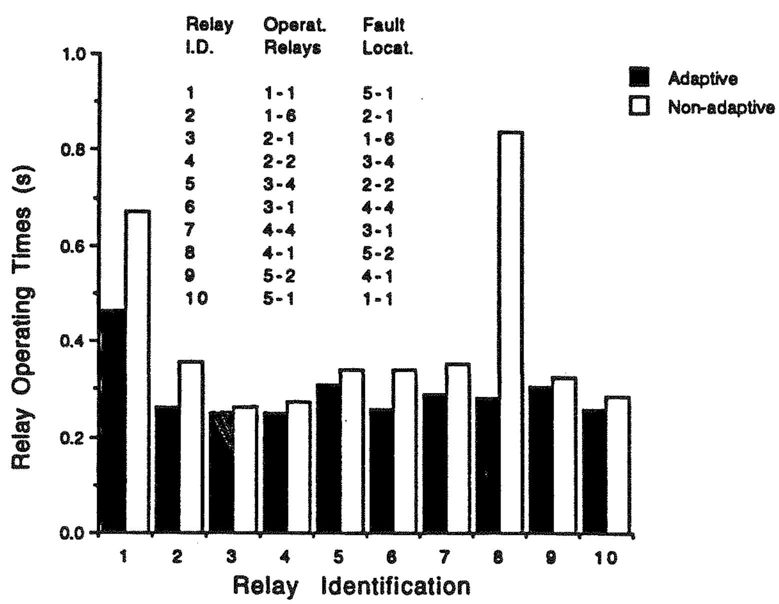

Figure 8 Relay operating times using adaptive and non non-adaptive approaches during MNLG-2.

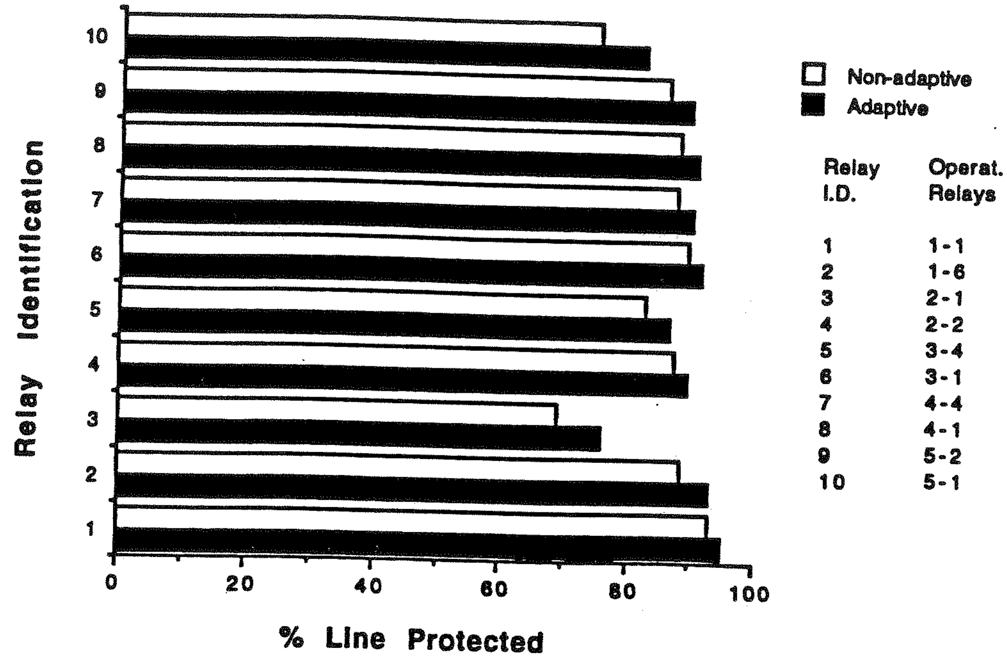

Figure 9 Percent line protected by instantaneous relays during MNLG-2.

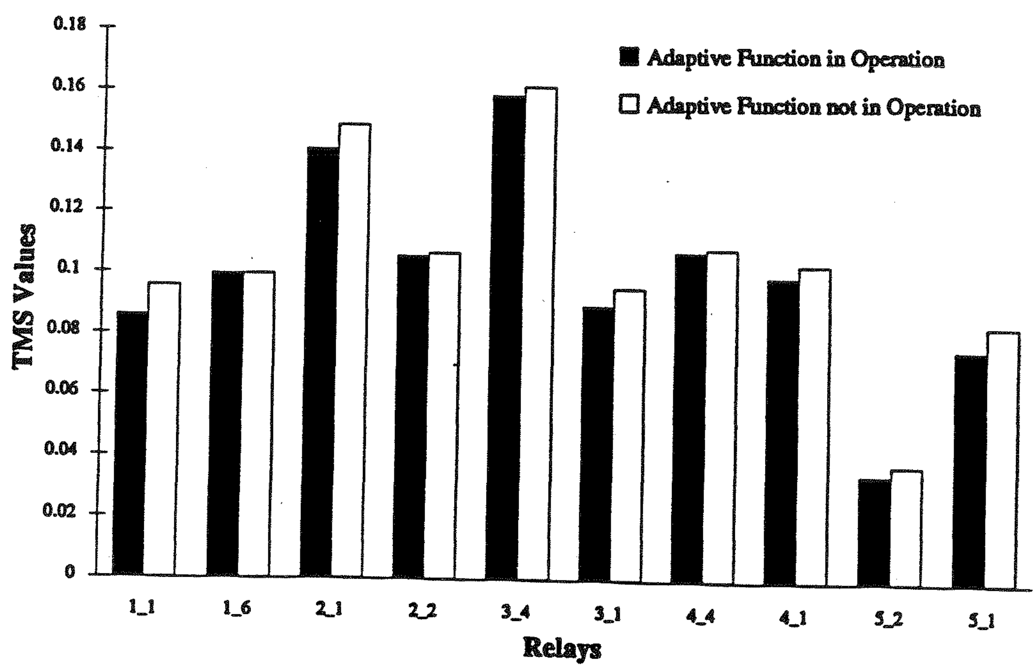

Figure 10 Locally Vs. Centrally estimated TMS values when line 1-20 open.

APPENDIX-A

Table - A

Line Impedance			Bus Load (Maximum Loading Condition)		
Line, bus to bus	Resistance % on 10 MVA base	Reactance % on 10 MVA base	Bus	Real Power (MW)	Reactive Power (MVAR)
1-6	0.723	0.270	1	19.48	9.43
6-7	0.683	1.064	6	0.0	-2.4
7-8	0.243	0.374	7	10.93	5.29
8-2	1.218	0.861	8	1.35	-.546
2-9	1.047	3.333	2	13.5	6.53
9-10	0.209	0.653	9	6.3	3.051
10-11	0.077	0.240	10	0.0	-1.2
11-3	0.591	1.841	11	0.315	0.152
3-12	0.555	1.734	3	11.02	5.336
12-13	0.663	2.160	12	0.18	0.087
13-14	0.357	1.163	13	0.81	0.392
14-15	0.149	0.463	14	5.21	2.524
15-4	1.042	3.248	15	0.0	-1.2
4-16	0.688	1.842	4	13.73	6.647
16-17	1.024	3.180	16	1.8	0.872
17-18	0.400	0.616	17	2.7	1.307
18-19	0.165	0.498	18	6.367	3.084
19-20	0.165	0.498	19	0.0	-1.2
20-21	0.804	1.759	20	1.035	0.501
21-5	0.427	1.065	21	8.704	2.415
5-22	0.536	1.241	22	2.78	1.349
22-23	0.251	0.407	23	4.5	0.984
23-24	0.337	0.653	24	0.28	0.135
24-25	0.110	0.171	25	1.62	0.784
25-26	0.173	0.266	26	0.9	0.436
26-27	0.521	0.801	27	3.303	3.997
27-28	0.464	1.402	28	2.78	1.349
28-1	0.386	1.048			
1-20	0.585	0.817			

Note: During minimum loading, bus loads are half of the listed loads.