UNIVERSITY OF KWA ZULU NATAL(UDW)

ASSESSMENT OF THE ELECTRICAL PERFORMANCE OF THE CAHORA BASSA HVDC SCHEME

BY

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ABSTRACT

The aim of this study was to assess the electrical performance of the Cahora Bassa HVDC scheme. For practical reasons a database was developed to hold and analyse the performance data. Microsoft® Access 2002 relational database management system was chosen for this work. The principle of simplicity and flexibility were used in the design of the database.

The Apollo year 2002 faults data was populated into the database. The database stored the information in a format that enables the user to extract results and the information required by Cigré. The Cigré Working Group 14 collects performance information from all the participating HVDC schemes around the world annually.

The Apollo converter station's 2002 performance data was compared to other similar HVDC schemes that submitted to Cigré in the year 2002. In addition performance trends were drawn from similar schemes that submitted to Cigré over the past years. The Apollo performance data is quite comparable to other similar schemes in 2002 and over the past years.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The reliability of an electrical system can best be gauged after its performance is assessed and compared to similar electrical systems around the world based on the same standards. The International Council on Large Electric Systems (Cigré) collects electrical performance information from all participating HVDC (High Voltage Direct Current) systems around the world. This information can be used world wide for the planning, design, construction and operation of new projects. The sharing of this information is also useful for future projects in HVDC. [1]

The reporting of the performance helps in benchmarking. For this to be possible the reporting is standardised. System description, main circuit data and a simplified one-line diagram are the general information required from every system. The inclusion of the operational performance data such as reliability, availability and maintenance is also important. [1]

Until now no performance data is readily available for the Cahora Bassa HVDC scheme. This project aims to collect all the relevant data and to compile it into a coherent format in a database which will comply with international requirements. Also the information which is available has not been refined as yet in order to comply with international standards.

The faults which occurred on the Cahora Bassa were recorded by the control room operators on the Daily Log Record. This information however, was not electronically captured. Consequently, it is not an easy task to determine the performance levels of this scheme as it would take many hours of sifting through reports as well as completing several calculations in order to derive the performance statistics required as defined by Cigré. It was therefore decided to create a database in which data can be stored and retrieved for analysis, thus reducing the amount of time required in determining the performance statistics of the line.

The main objective of the research is to address the following questions:

- How does the HVDC Transmission line performance compare to similar HVDC lines throughout the world?
- To what extent does its performance level meet international standards?
- What are the main factors affecting the present performance?
- Is the currently used procedure for fault logging adequate?

This study will involve the design process of the database which, will simplify the task of determining the performance statistics of an HVDC transmission system, in line with Cigré requirements.

The broader system performance is measured by five main parameters.[1] These parameters are the output of the calculations that are carried out in the database. These parameters are:

- Energy Transmitted [GWh],
- Energy Utilization %,
- Energy Availability %,
- Energy Unavailability %,
- Forced Outages,
- AC system Faults and Commutation Faults.

1.2 OUTLINE OF THE WORK CARRIED OUT

1.2.1 A literature survey was carried out to form a foundation for the understanding of the parameters used in performance determination. The IEC (International Electrotechnical Commission) standards and Cigré protocol were consulted. A comparison of different databases was carried out; as a result a course in Microsoft® Access 2002 was completed. The literature that was reviewed covered the following topics:

- The Cigré, Protocol for Reporting the Operational Performance of

HVDC Transmission systems

- Survey of the reliability of HVDC systems throughout the world.
- Recommissioning experience with Cahora Bassa system.
- The reports of the Working Group 14.04.
- System Performance Reports

1.2.2 Database Development

The work describes the database design. It then looks at how data is populated in the database followed by the calculations done in the database. A comparison is then done to benchmark Cahora Bassa with other similar schemes elsewhere. Conclusions are drawn and further areas of research that came out of this work are recommended.

1.3 ANALYSIS TOOLS AND SYSTEM PERFORMANCE PARAMETERS

This section looks into the analysis tools used in the database as well as the performance indices as specified by Cigré. The considered parameters are: Energy Transmitted [GWh], Energy Utilization %, Energy Availability %, Energy Unavailability %, Forced Outages, AC system Faults and Commutation. These are taken from Cigre Working Group 04 Protocol. They are discussed in detail below. [9]

1.3.1 Energy Transmitted [GWh]

Two terms are used when Energy Transmitted is analysed. That is; Maximum Continuous Capacity and Outage Capacity. They are defined by Cigré as follows [9]:

1.3.1.1 Maximum Continuous Capacity (P_m)

The maximum capacity (MW), excluding the added capacity available through means of redundant equipment, for which continuous operation under normal conditions is possible, is referred to as the maximum continuous capacity. [9]

For two-terminal systems reporting jointly, the maximum continuous capacity is referred to a particular point in the system, usually at one or the other convertor station. Two-terminal systems reporting separately, the maximum continuous capacity refers to the rating of the individual convertor station. In a case when the maximum continuous capacity varies according to seasonal conditions, the highest value shall be used as the capacity for the purpose of reports prepared according to this Protocol. For Apollo the maximum continuous capacity is 1200MW, which is the highest value. [9]

1.3.1.2 Outage Capacity (P_o)

The capacity reduction in Megawatts which the outage would have caused if the system were operating at its maximum continuous capacity (P_m) at the time of the outage. For two-terminal systems reporting jointly, the outage capacity is referred to the same point in the system used for determining P_m. [9]

1.3.2 Energy Utilization Percentage

Energy utilization is a factor giving a measure of the energy actually transmitted over the system. For two-terminal systems, the energy utilization is calculated based on the same point in the system used for determining P_m.[9]

$$Energy\,Utilization\,\% = \left[\frac{Total\;Energy\,Transmitted}{(P_m \times P_H)}\right] \times 100 \qquad \text{Equation 5.1 [9]}$$

Where

$Total\ Energy\ Transmitted = Energy\ Exported + Energy\ imported$ Equation 5.2 [9]

P_m: Maximum continuous capacity in MW

P_H: Period hours

Energy Imported and Energy Exported are expressed in Megawatt hours and both referred to the point at which Pm is defined.

1.3.3 Energy Availability %

A measure of the energy which could have been transmitted except for limitations of capacity due to outages is referred to as energy availability.

For two-terminal systems reporting jointly, the energy availability is calculated based on the same point in the system used for determining P_m. [9]

$Energy\ Availability\% = 100 - Energy\ Utilization$ Equation 5.3 [9]

1.3.4 Energy Unavailability %,

A measure of the energy which could not have been transmitted due to outages is referred to as the energy unavailability. For two-terminal systems reporting jointly, the energy unavailability is calculated based on the same point in the system used for determining P_m. For two terminal systems reporting separately, the energy unavailability is calculated separately for each individual convertor station.

$$Energy\ Unavailability\%,\quad EU = \frac{EOH}{P_H} X100$$ Equation 5.4 [9]

$$Forced Energy\ Unavailability\%,\quad FEU = \frac{EFOH}{P_H} X100$$ Equation 5.5 [9]

$$Scheduled Energy\ Unavailability\%,\quad SEU = \frac{ESOH}{P_H} X100$$ Equation 5.6 [9]

1.3.5 Forced Outages

1.3.5.1 *Outage* - The state in which the HVDC System is unavailable for operation at its maximum continuous capacity due to an event directly related to the converter station equipment or dc transmission line is referred to as an outage. Failure of equipment not needed for power transmission shall not be considered as an outage for purposes of this report. AC system related outages are recorded but not included in HVDC system reliability calculations. For purposes of this report, outages taken for major reconfiguration or upgrading such as addition of converters are not be reported. [9]

1.3.5.2 *Scheduled Outage* - An outage, which is either planned or which can be deferred until a suitable time, is called a scheduled outage. [9]

Scheduled outages can be planned well in advance, primarily for preventive maintenance purposes such as annual maintenance program. During such planned maintenance outage, it is usual to work on several different equipments or systems concurrently. It is not necessary to allocate such outage time to individual equipment categories. Only the elapsed time should be reported in Table 2SS as "PM". [9]

Classified under the scheduled outage category are also outages for work which could be postponed until a suitable time (usually night or weekend) but cannot be postponed until the next planned outage. Equipment category code in Table 2SS should be used to identify the affected equipment. This includes discretionary outages based on operating policies, owner's preference and maintenance of redundant equipment. It must be noted that if the scheduled outage is extended due to additional work which would otherwise have necessitated a forced outage, the excess period is counted as a forced outage. [9]

1.3.5.3 *Forced Outage* - The state in which an equipment is unavailable for normal operation but is not in the scheduled outage state, is referred to as a forced outage. Trips however, are defined as a sudden interruption in transmission by automatic protective action or manual emergency shutdown.[9]

Included in this category of forced outages are other unexpected HVDC equipment problems that force immediate reduction in capacity of HVDC stations but do not cause or require a trip. Also in this category are outages caused by start-up or de-block delays. [9]

1.3.6 AC system Faults and Commutation.

1.3.6.1 *Recordable A.C. System Fault* - In this context, an a.c. system fault is one which causes one or more of the inverter a.c. bus phase voltages, referred to the terminals of the harmonic filter, to drop immediately following the fault initiation below 90 per cent of the voltage prior to the fault. Note also that in this context, ac system faults at, or near, the rectifier are not relevant and should not be included in this reporting. An exception to this rule is a special case where the network topology dictates that an ac fault near the rectifier also produces a simultaneous recordable fault at the inverter. [9]

1.3.6.2 *Commutation Failure Start CFS(A)* - The initiation or onset of commutation failure(s) in any valve group immediately following the occurrence of an ac system fault, regardless of whether the ac fault is "recordable" as defined in 5.6.1 above. Do not include in here commutation failures as a result of control problems or switching events. [9]

1.3.6.3 *Commutation Failure Start CFS(B)* - The initiation or onset of commutation failure(s) in any valve group as a result of control problems, switching events or other causes, but excluding those initiated by ac system faults under 5.6.2 above. [9]

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

2.1 Mercury-Arc Valves

In 1882 Marcel Deprez transmitted about 1.5kW across a distance of 35 miles at 2kV. Alternating Current (A.C) usage increased in the years that followed because of the availability of transformers and development of induction motors. In 1889 R Thury transmitted about 20MW at 125kV across a distance of 230km between Moutiers and Lyon. This system operated at constant current and was used as a reinforcement of an existing A.C system.[2]

Some of the noteworthy details of developments which resulted in the HVDC (High Voltage Direct Current) transmission technology are as follows:

a. There was the Hewitt's mercury–vapour rectifier, which appeared in 1909, and the introduction of grid control in 1928, provided the basis for controlled rectification and inversion.

b. Prior to 1940, experiments were carried out in America with thyratrons and in Europe with mercury pool devices. [2]

In Sweden, by 1939, Dr. Uno Lamm had invented a system of grading electrodes with a single-phase valve construction. Dr. Uno Lamm's work provided a basis for larger peak inverse withstand voltages. This High Voltage valve had a mercury-pool cathode with a cathode spot. It was maintained by means of an auxiliary arc. This arc caused a continuous emission of electrons. The anode was designed to eliminate the reverse emission of electrons. [2]

During firing and blocking the charge carriers strike the walls and that resulted in material depositing through the valve. As a result there were problems; firstly, the valve required a lot of maintenance. Secondly, it appeared that the maximum direct voltage that could be attained by the mercury-arc bridge was now limited to 150kV. [2].

These graded electrode mercury-arc valves were further developed towards the end of the 1940s, such that by 1954 the first commercial application of HVDC was in operation using these graded electrode mercury-arc valves. [2]

In 1950 an underground HVDC transmission system over a distance of about 112km was in operation in the then USSR (Union of Soviet Socialist Republics). The system operated between Moscow and Kashira and transmitted about 30MW at 100kV.[2]

The first commercial HVDC link was built between mainland Sweden and the island of Gotland in 1954. The transmission line was a 20MW underwater cable operating at 100kV. The first HVDC overhead transmission line was the ±400kV Volgograd-Doubass line in the Soviet Union, commissioned in the 1962 to 1965 period [2]. Table 2.1 lists the systems that were developed using the mercury arc valve technology.

Table2.1 Mercury Arc Valve Technology HVDC Schemes [3]

Year commissioned	System Name	Power [MW]	DC Voltage [kV]	Overhead Line/ Cable [km]
1951	Moscow-Kashira	30	±100	100
1954	Gotland I	20	100	96
1961	English Channel	160	±100	64
1962-65	Volgograd- Donbass	720	±400	470
1965	Inter-Island	600	±250	609
1965	Konti- Skan I	250	250	180
1965	Sakuma	300	±125	0
1967	Sardinia	200	200	413
1968	Vancouver I	312	260	69
1970	Pacific Intertie	1440	±400	1362
1973-77	Nelson River Bipole1	1620	±450	892
1975	Kingsnorth	640	±266	82
1982	Pacific Intertie	1600	±400	1362

In North America, the first overhead transmission lines at EHV (Extra High Voltage) were commissioned in the early nineteen seventies. These were the Pacific Intertie in the United States of America, and the Nelson River Project in Canada. After that time other systems were commissioned under various system voltages up to ±533kV. [4]

Since that period several schemes are no longer in operation. The Moscow-Kashira, Sweden-Gotland, English Channel, Sakuma, Sardinia-Italy and Kingsnorth schemes have beed decommissioned. The Pacific Intertie scheme was taken out of service in 1994. Two of the schemes have since replaced the mercury arc valves with thyristors. The Volgograd- Donbass scheme in 1977, and the Nelson River Bipole1 in 1993. The Nelson River Pole1 thyristor valves replaced the mercury-arc valves in all three valve groups of this pole only. In pole 2 mercury-arc valves are still being used. [3]

2.2 Thyristor Valves

In 1970 utilities needed to decide whether to continue with mercury-arc valves or accept the relatively untried thyristor technique. Investigations into the design and performance of prototype mercury-arc valves in Germany had indicated that, as far as their characteristics were concerned, mercury-arc valves suffered from physical limitations, which could be overcome at a lot of time and cost. [5]

In addition, availability reports drew attention to the susceptibility of mercury-arc valves in the existing installations. They were susceptible to short duration outages, tending to confirm the suspicion that thyrisors were more dependable in operation. Factors relating to relative ease of operation and maintenance helped the utilities to finally decide on the oil-cooled and oil-insulated thyristor valves for outdoor installation. [5] Table 2.2 shows the systems that use the thyristor valves. The Back-to-back (B-B) HVDC Schemes have no Transmission lines.

The first experimental valves were air-cooled and air-insulated. There were others valves which were considered more powerful; they were oil-cooled and air-insulated. After that there were valves which were oil-cooled and oil-insulated. At that time, the Cahora Bassa had the highest transmission capacity of 1920MW and highest transmission voltage of ±533kV with oil-cooled and oil-insulated thyristor. [5]

Table 2.2 Thyristor Valve Technology HVDC Schemes [3]

Year Commissioned	System Name	Power [MW]	DC Voltage [kV]	Cable/ Conductor Length [km]
1983/87	GOTLAND II-III	260	±150	96
1972	EEL RIVER	320	2x80	B-B
1976/77/93	SKAGERRAK 1-3	1050	250/350	240
1968/77/79	VANCOUVER	682	-0.928571429	74
1977	SHIN-SHINANO	300	125	B-B
1977	SQUARE BUTTE	500	±250	749
1977	DAVID A. HAMIL	100	50	B-B
1978	CAHORA-BASSA	1920	±533	1440
1973/93	NELSON RIVER 1	1854	-0.926	890
1985	NELSON RIVER 2	2000	500	940
1979	C.U.	1000	±400	702
1979	HOKKAIDO-HONSHU	600	250	167
1981	ACARAY	50	26	B-B
1981	VYBORG	355	1x170 (±85)	B-B
1982	ZHOU SHAN PROJECT	50	100	42
1982	INGA-SHABA	560	±500	1700
1983	DUERNROHR	550	145	BB
1983	GOTLAND II	130	±150	100
1987	GOTLAND III	260	±150	103
1983	EDDY COUNTRY	200	82	B-B
1984	CHATEAUGUAY	1000	2x140	B-B
1985	OKLAUNION	220	82	B-B
1984	ITAIPU 1	1575	±300	785
1985	ITAIPU 1	2383	±600	
1986	ITAIPU 1	3150	±600	
1984	PAC INTERTIE	2000	±500	1362
1985	BLACKWATER	200	57	B-B
1985	HIGHGATE	200	56	B-B
1985	MADAWASKA	350	140	B-B
1985	MILES CITY	200	82	B-B
1986	BROKEN HILL	40	2x17 (±8,33)	B-B
1986	I.P.P.(INTERMOUNTAIN)	1920	±500	784
1986	CROSS CHANNEL BP 1+2	2000	±270	71
1986	DES CANTONS COMERFORD	690	±450	172
1986	SACOI	200	±200	415
1992	SACOI	300		
1987	ITAIPU 2	3150	±600	796
1987	VIRGINIA SMITH	200	50	B-B
1988	KONTI-SKAN 2	300	±285	150
1989	GEZHOUBA SHANGHAI	600	500	1000
1990	GEZHOUBA SHANGHAI	1200	±500	
1989	VINDHYACHAL	500	70	150
1989	PACIFIC ITERTIE	3100	500	1361
1989	Mc NEILL	150	42	B-B
1989	FENNO-SKAN	500	400	233
1989	SILERU-BARSOOR	400	±200	196
1990	HYDRO QUEBEC NEW ENG	2000	±450	1500
1992	RIHAND-DELHI	1500	±500	814

Table 2.2 Thyristor Valve Technology HVDC Schemes [3] Continued

Year	System Name	Power [MW]	DC Voltage [kV]	Cable/ Conductor Length [km]
1992	NICOLET TAP	2000		
1993	ETZENRICHT	600	145	BB
1993	VIENNA SOUTH EAST	600	160	BB
1993	DC HYBRID LINK			
1987	URUGUAIANAI	54	18	B-B
1994	BALTIC CABLE	600	450	255
1995	WELSH	600	162	B-B
1995	KONTEK	600	400	171
1998	LEYTE-LUZON	440	350	443
1997	HAENAM-CHEJU	300	±180	101
1997	CHANDRAPUR RAMAGUNDUM	1000	2x205	BB
1998	CHANDRAPUR PADGHE	1500	±500	736
1998	VISAKHAPATNAM	500	205	BB
1999	MINAMI-FUKUMITSU	300	125	BB
1999	SWEPOL	600	450	230
1999	KAALAMO	40	20	BB
1999	NORTH-SOUTHEAST	1000		
2000	KII CHANNEL	1400	± 250	BB
2000	GREECE-ITALY	500	400	300
2000	TIAN-GUANG	1800	500	903
2000	GARABI I	1100	±70	B-B
2002	GARABI II	1100	±70	BB
2000	RIVERA	70		B-B
2001	HIGASHI-SHIMIZU	300	±125	BB
2001	MOYLE INTERCONNECTOR	500	250	64

In the Cahora Bassa scheme each valve module contains 14 thyristors arranged in pairs, with their respective heat sinks, to form two columns. This arrangement allows each thyristor cooled on both sides. At a rated continuous direct current of 1800A and a maximum oil inlet temperature of 40°C, the valve is able to withstand the following three types of faults:

1. Short-circuit faults in the converter station followed by a closure of the over-current diverters.

2. Earth fault on the D.C (Direct Current) line cleared by gate control.

3. Commutation failure with line discharge (which may be due to three phase short circuit on the busbar). [6]

2.3 CAHORA BASSA

There are different configurations that can be used when designing an HVDC system. When comparing schemes it is important to compare similar schemes. The Apollo Cahora Bassa has the following specifications and configuration.

The system mainly transmits bulk power from the hydro electric power station on the Cahora Bassa dam to the Eskom network in South Africa and the Southern Mozambique network. From the hydro power station 220kV transmission lines are used to transmit about 2000MW of power for about 6km to Songo rectifier station. At Songo rectifier station the power is converted to D.C and then transmitted to Apollo inverter station using two Monopolar D.C lines at ±533kV. The lines are about 1440 km in length and about 1 km apart. At Apollo inverter station the power is converted to A.C and transmitted in the Eskom grid at 275kV. [7]

2.4 FURTHER DEVELOPMENTS

2.4.1 Before the Nineteen Eighties

In this period there were twenty-one HVDC systems in operation. This number covered a range of voltages and various power transmission capabilities. Both the mercury-arc valve and thyristor valve technologies were in use. Table 2.3 shows the schemes with the lowest and highest voltage levels as well as lowest and highest power transmission capabilities. [8]

Table 2.3 HVDC Technological Developments Before the 1980s [8]

Capability	**Scheme Name**	**Country**	**Voltage [kV]**	**Power [MW]**	**Year Commissioned**
Lowest V	David A Hamil	USA	**50**	100	1977
Highest V	Cahora Bassa	South Africa/ Mozambique	**±533**	1920	1977
Lowest MW Transmitted	Gotland	Sweden Mainland	100	**30**	1954
Highest MW Transmitted	Cahora Bassa	South Africa/ Mozambique	±533	**1920**	1977

2.4.2 During the Nineteen Eighties

The number of HVDC systems that were commissioned in the nineteen eighties was as many as forty two. The number of HVDC systems doubled in this period compared to that of the systems in the seventies. The voltage levels ranged from 26kV to about ±600kV. Table 2.4 lists Acaray scheme in Paraguay as the scheme with the lowest power transmission capability. There are however two other schemes that could have been equally listed they are Tap in France and Uruguaiana in Brazil and Argentina. [8].

Table 2.4 HVDC Technological Developments During the 1980s [8]

Capability	Scheme Name	Country	Voltage [kV]	Power [MW]	Year Commissioned
Lowest V	Acaray	Paraguay	**26**	50	1981
Highest V	Itaipu		**±600**	2383	1985
Lowest MW Transmitted	Acaray	Paraguay	26	**50**	1981
Highest MW Transmitted	Itaipu		±600	**6300**	1986

2.4.3 During the nineteen nineties

During this period there were about twenty four HVDC systems that were commissioned. The systems with the highest voltage level among these twenty four were the Gezhouba-Shanghai at ±500kV and Rihand-Delhi at ±500kV. In Table 2.5 only Rihand-Delhi is listed. Two systems had the highest power transmission capability. These systems are Hydro Quebec and Nicolet Tap and both are able to transmit about 2000MW. [3]

Table 2.5 HVDC Technological Developments During the 1990s [3]

Capability	Scheme Name	Country	Voltage [kV]	Power [MW]	Year Commissioned
Highest V	Rihand-Delhi		**±500**	1500	1992
Highest MW Transmitted	Hydro Quebec	Canada	±450	**2000**	1990

There have been significant improvements in the system designs with reference to voltage, cable and overhead line length as well as power transmission capabilities. There are notable milestones which include the Itaipu system with a voltage of 600kV, the largest HVDC scheme in the world.The Inga Shaba system in Zaire with a transmission line length of about 1700km. The Itaipu system again is also noted for the milestone of 6300MW power transmission capability.

Due to many reasons some of the systems listed in this chapter have been put out of service, others have been upgraded but most are still in service. [8]

2.5 CIGRE REPORTING SYSTEM

Working group 04 of the Cigré Study Committee 14 was established after there was recognition that the experience gained in HVDC transmission systems could be of great value throughout the power engineering industry, if it was properly documented. This working group concentrates on Performance of HVDC Schemes, and its mandate also includes the obligation to collect information on all systems in commercial service each year. [9]

The great value of this collected information is used in the planning, design, construction and operation of new HVDC projects. Coupled with these reasons, is the sharing of operational performance data that benefits all those dealing with operating existing HVDC systems or those planning new HVDC systems. This report is prepared in a standardized format to ensure that a consistent method of comparing performance data is established. [9]

There are two categories of information that the Working Group collects. The general information and the operational performance data. Under the general information the following details are considered for each system:

- System description
- Main circuit data
- And a simplified one-line diagram.

Under the operational performance data the following information is collected:

- Reliability,

- Availability
- And maintenance statistics.

The Working Group 04 puts together the performance information of all the systems that report general and operational data every two years in a CIGRÉ paper entitled "A Survey of the Reliability of HVDC Systems Throughout the World." [9]

CHAPTER 3

DATABASE DESIGN

The database is a tool used to store and analyse data. These two components influenced the design. The storing of data is made easy by using a Microsoft® Windows based database system, Microsoft® Access2002. Access2002 is flexible and allows for easy interfacing with common spreadsheets and word processor applications. The availability of reports and queries makes the analysis of data clearer. This chapter looks into the design process and discusses the components that make up the database. [10]

The three main factors that were taken into consideration in the design of the database are:

- A database that is easy to use. It is for this reason that a Microsoft® Windows based database system, Microsoft® Access2002 was chosen.
- A program that is flexible enough to allow for easy interfacing with the common spreadsheets and word processing programs, as well as comprehensive analysis capabilities.
- A format for the tables of the Cigré Protocol for Reporting the Operational Performance of HVDC Transmission systems. The January 1997 revision of the protocol is used in this work [9].

Microsoft® Access2002 is a relational database management system. As a principle; how the data is stored in the database determines the limit of how much can be done with the data. The data is stored in separate tables. This allows for flexibility when extracting data. In addition it makes managing data easier and duplication is eliminated. Each table thus deals with a specific topic, this is the design philosophy chosen for this work. Any number of tables can be linked for the purpose of analysing and filtering information The table that deals with the topic of time, contains the time of fault as well the date. The table that deals with energy only contains energy information. So is the table that contains the classification of faults.

The tables are linked using a common field in each table. We chose the ORN field to be the common field that links all the tables. The one-to-one relation between the tables was maintained as a principle for all the tables in the database. Linking tables using many-to-many relation is not possible. All the other components of the database are discussed in this chapter.

Tables covering the following areas were completed.

- Forced Outages Substation,
- Scheduled Outages Substation,
- Overhead line Protection Operation,
- AC System Faults,
- Thyristor Failures, and
- Forced Outage Summary.

Figure 3.1 shows the Main Menu of the database. The Main Menu window consists of two sides. The right hand side is the Input and the left hand side of the window display the output of the database. At the top left hand corner is the View Outage Log button that opens a copy of the Cigré Standard Log Form. The other buttons open Table One to Table Six.

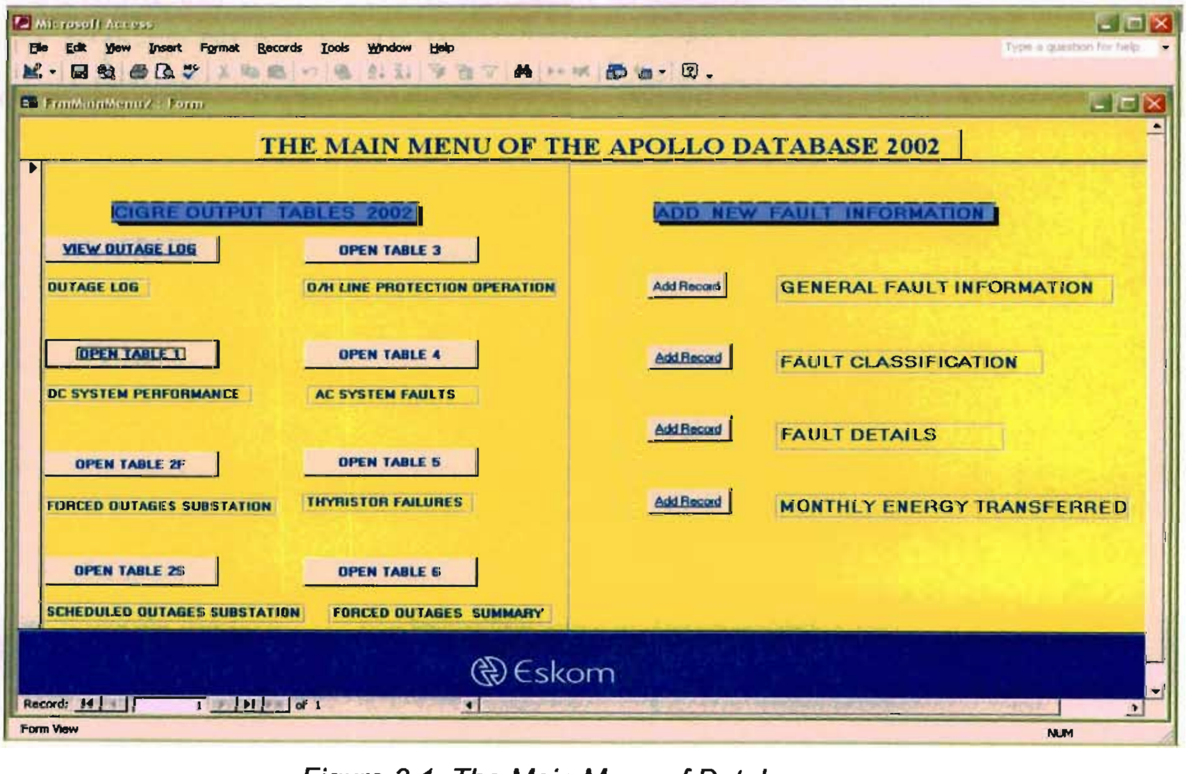


Figure 3.1. The Main Menu of Database

3.1 General Fault Information Table

The data was stored in four different tables. The first is the General Table called TblGenFaultInfo2002. Figure 3.2 shows the Design View of the General Table. This table contains general information about the fault that is recorded. The first field contains the Primary Key which is a unique number that distinguishes the fault. It is called ORN which stands for Outage Reference Number. This is the field that is used to link the same fault information to all the other tables in the database.

The time and date fields are designed to have input masks. The input masks help to keep the format consistent, allowing the user to input data and time easily. The date format is *yyyy/mm/dd* and the time field format is *hh:mm*. The forward slashes automatically appear as the user types the date. For the time field the colon appears automatically.

The other fields are the Voltage Polarity and Faulted Station. For the Faulted Station field, the user selects the appropriate station from a drop down list. This was included in the design to save the user typing time. The station options are Apollo or Songo. The following three fields; Restart Attempts, Final Restart and AOD if Unsuccessful Fields are discussed in Chapter 4.

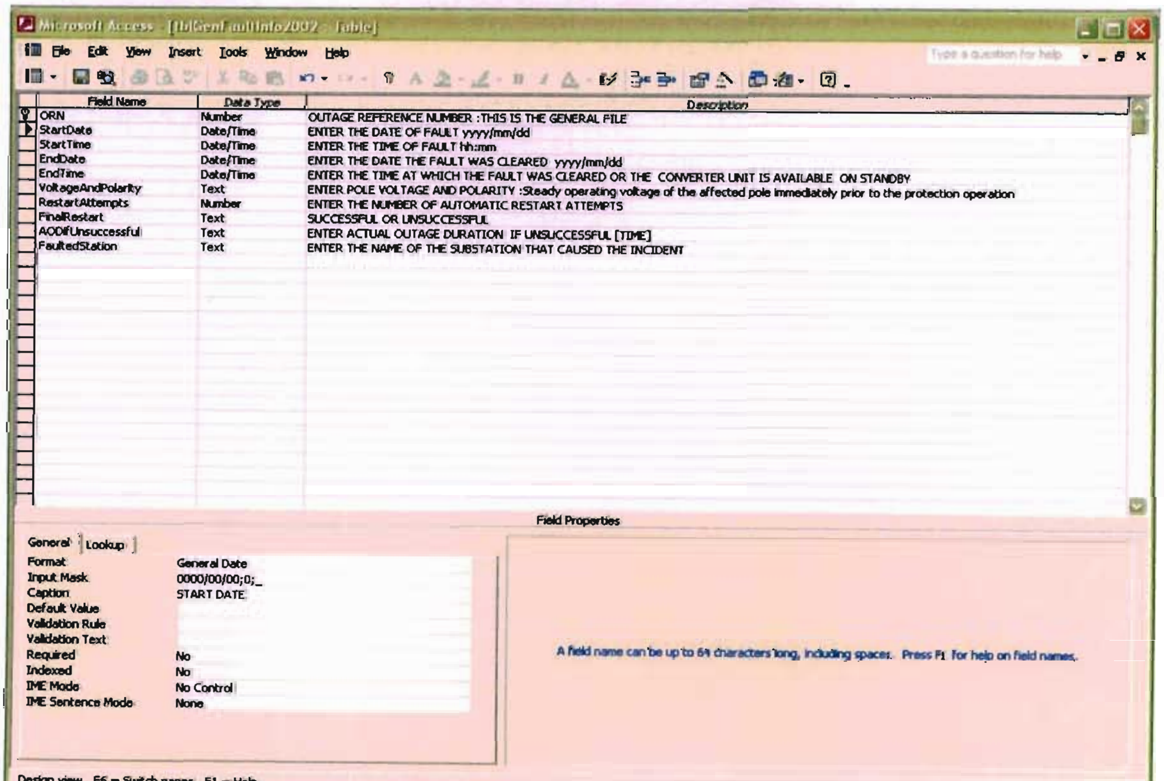


Figure 3.2 The Design View of the First Storage Table.

3.2 Main Fault Classification Table

The Main Fault Classification Table is the second data storage table. As in the previous table the first field is the Primary Key field. The user has a drop down list from which to select the class of fault. The fault is classified as one of the following five options; Human Error, Transmission Line, External AC System, Generation, or Unknown. The Design View of this data storage table is displayed in Figure 3.3. The user fills-in parts of this table depending on the class of fault. For example if the fault classification is Transmission Line then the user fills up the Line Distance field. This is demonstrated in Chapter 4.

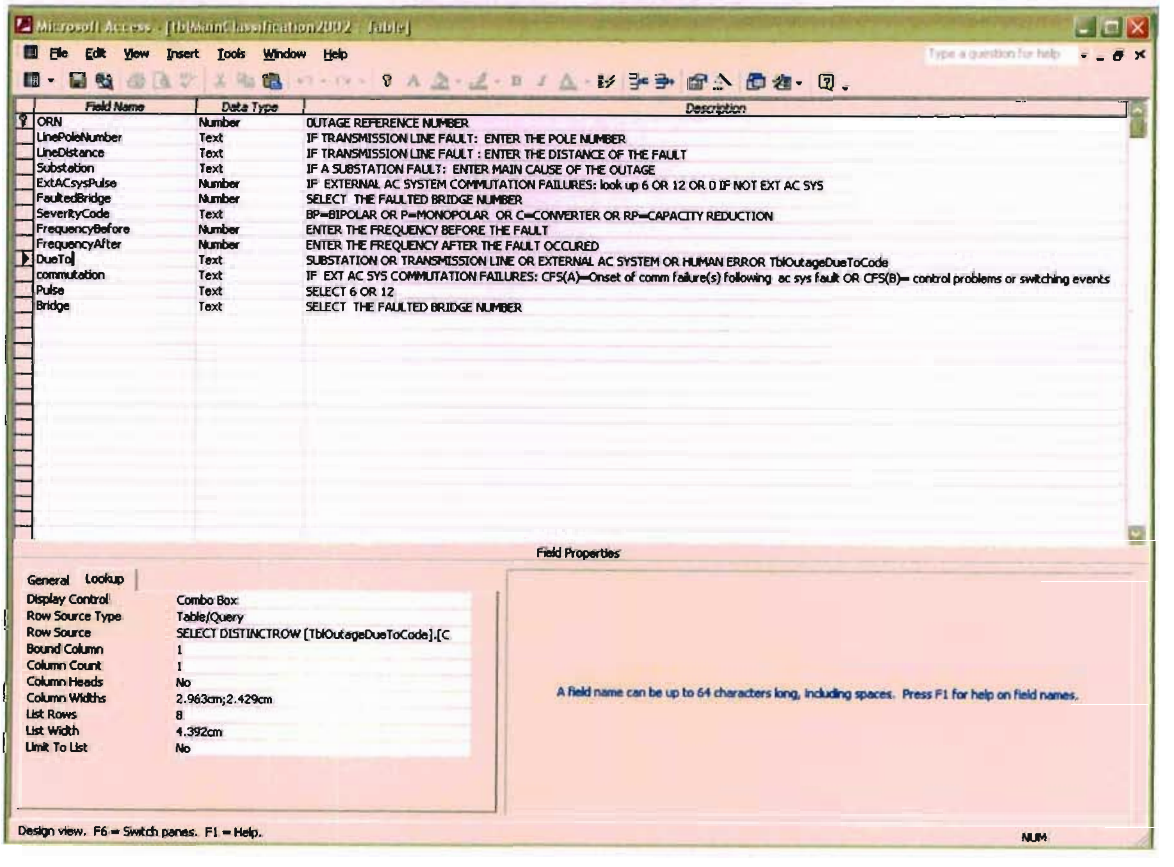


Figure 3.3 .The Main Classification of Faults Table

There are four general fields that are filled in for all the classes of faults. The first general field is the Faulted Bridge Number, which has a drop down list of numbers from one to eight. The second and third general fields are; System Frequency Before The Fault and Frequency After the Fault. The last general field is the Severity of the Fault. The user needs to indicate whether the fault resulted in a Bipolar, Monopolar, Converter or Capacity Reduction failure. These options are selected from a drop down menu.

3.3 Fault Details Table

This table contains the details of what caused the fault. Information on the restoration method as well as the lost energy is recorded here. Information on whether the equipment causing the fault was repaired, replaced or manually restarted is also recorded.

3.4 Energy Table

The last table is the energy details storage. There are three placeholders, that is, month, the number of hours in that month. And the Total Energy imported in that month.

3.5 Codes Table

Other tables were created to contain codes. The code tables contain all the information that is repeated in the tables. The codes are accessed when the user populates data as a result saving both storage space and typing time. There are ten such tables that were created to make the database user friendly and quick to populate. These code tables are:

- Commutation codes
- Bridge number
- Converter station names
- Months of the year
- Pulse number
- Restart attempts
- RSM restoration
- Severity of fault codes.
- Outage Code table, see Figure 3.4
- Outage Due to code table, see Figure 3.5.

These are the tables that store data. The analysis and calculations are carried out in the Microsoft® Access Queries. By definition Queries are used to view, change, and analyze data in different ways. They can also be used as a source of records for Forms and Reports[10]. In this database queries are used in calculating and arranging data into the correct Cigré format

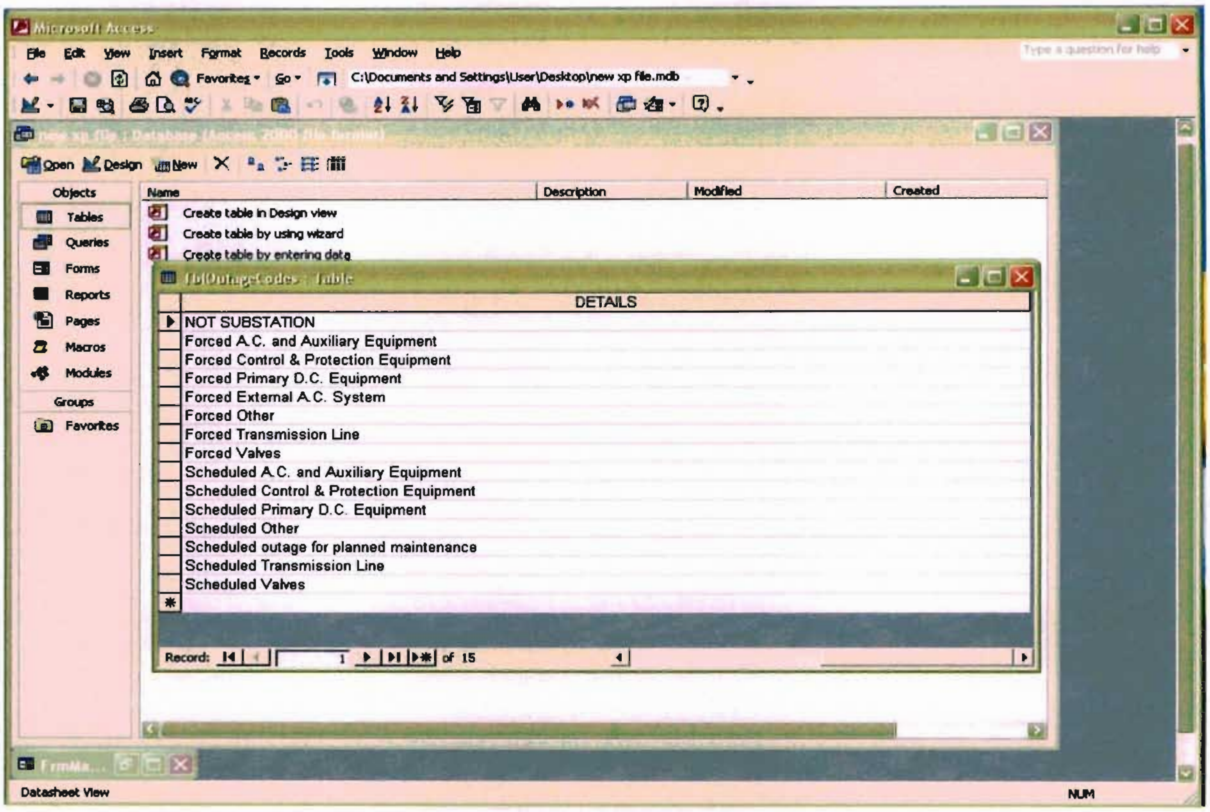


Figure 3.4 The Outage CodeTable

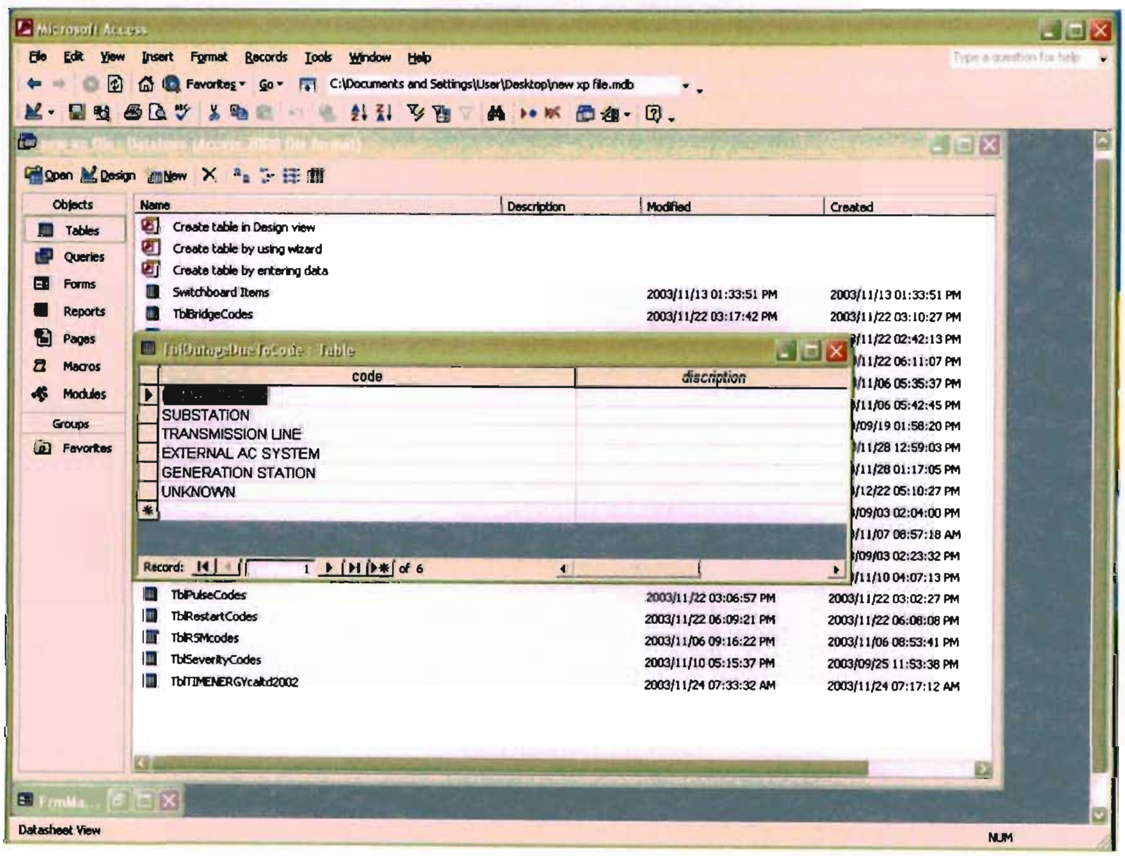


Figure 3.5 Outage Due to Code

3.6 Queries

There are six queries corresponding to the Cigré Tables in the protocol. In addition there are other queries that are only used for filtering and analysis.

The first query is the Outage Log Form query. The Outage Log Form is not required to be submitted to Cigré with the other tables. It is kept for record purposes only. A completed Outage Log Form can be viewed in Appendix B.

The second query serves as information holder for Cigré Table 1 (DC System Performance). The query is named in accordance with the Leszynski naming convention, which is used in this work. This convention is used to name objects and fields, making them easier to identify. According to the convention the object name is preceded by three letters. These letters are called the Tag. For an example the query in Figure 3.6 is called QryForTable1Calculation, where the tag is Qry. The tags for tables and reports are Tbl and Rpt respectively [11].

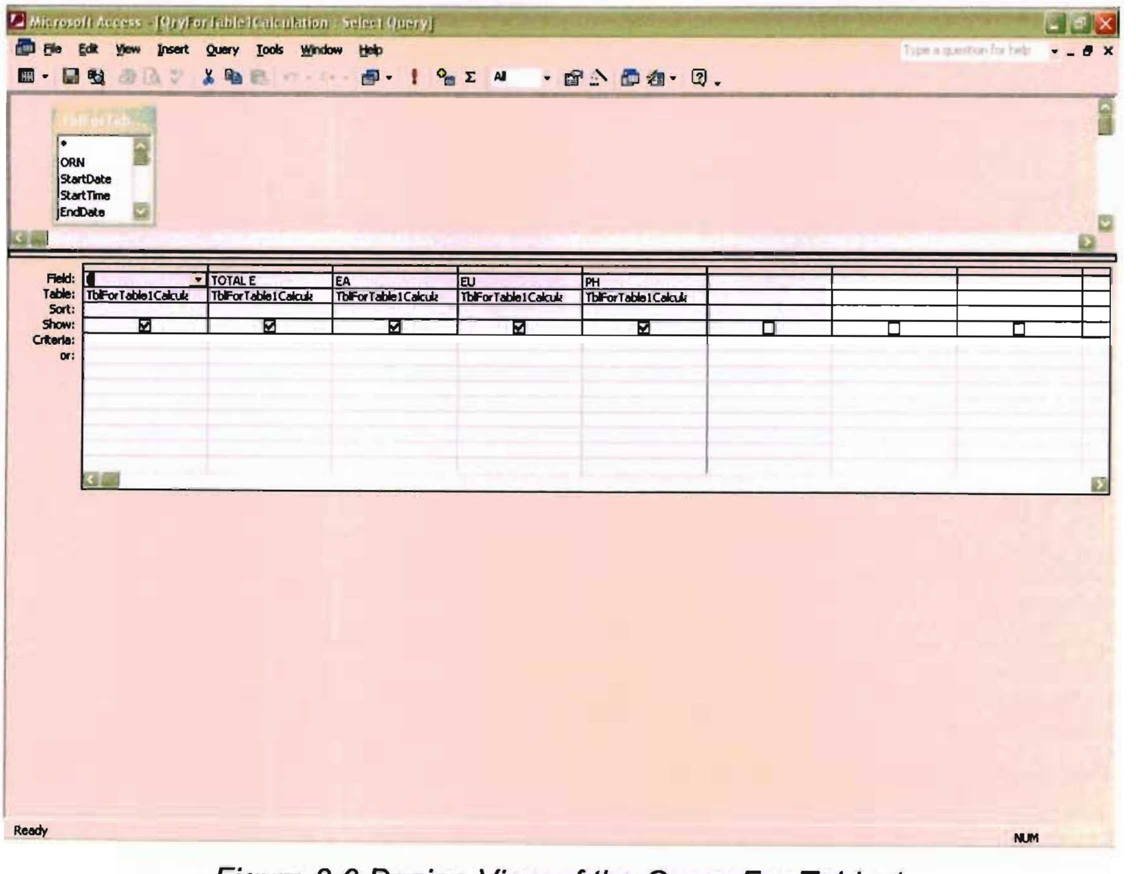


Figure 3.6 Design View of the Query For Table 1

This query uses table TblForTable1Calculation as its input. For this query there was no need to include selection criteria because all the fields are already filtered. These fields are used in Cigré Table 1 sections one, two and three.

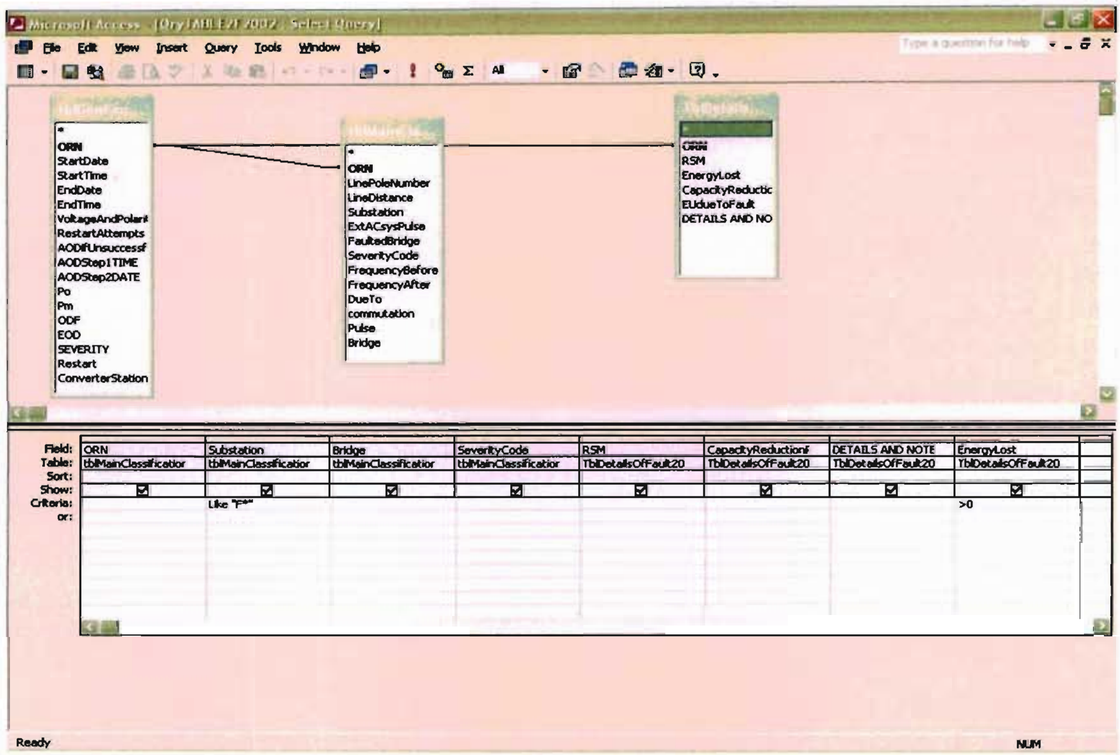
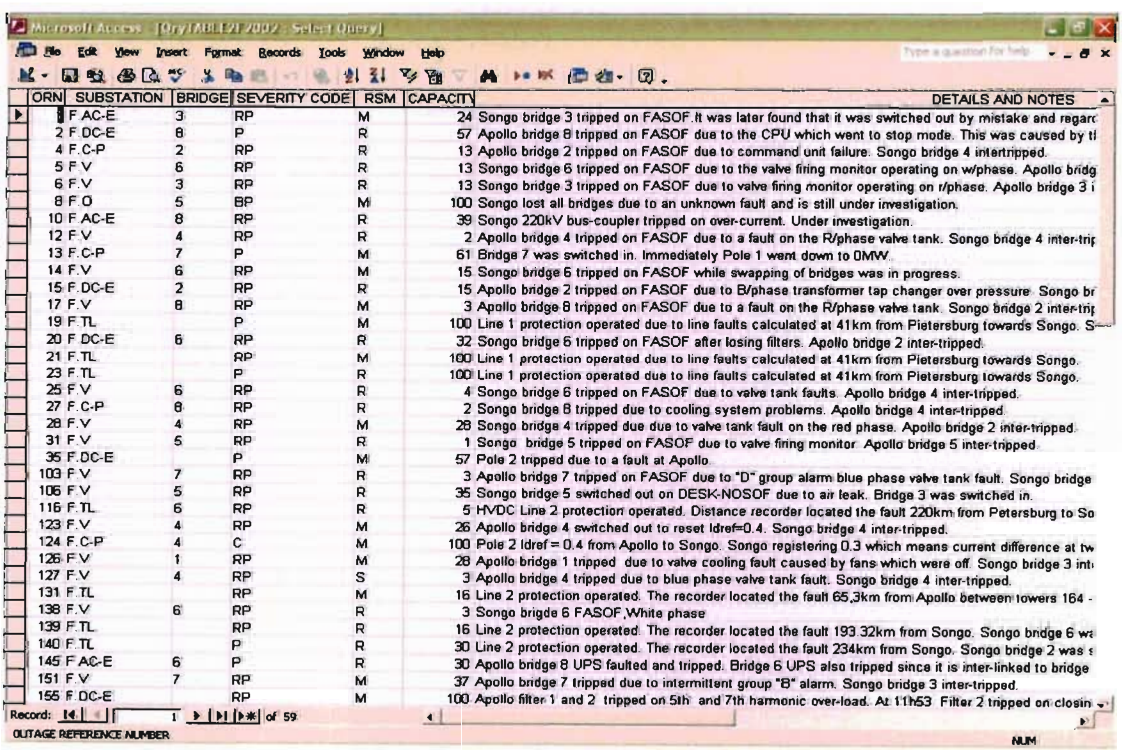


Figure 3.7 The Design View of the Query called QryTABLE2F2002



ORN	SUBSTATION	BRIDGE	SEVERITY CODE	RSM	CAPACITY	DETAILS AND NOTES
1	F.AC-E	3	RP	M	24	Songo bridge 3 tripped on FASOF.It was later found that it was switched out by mistake and regarc
2	F.DC-E	8	P	R	57	Apollo bridge 8 tripped on FASOF due to the CPU which went to stop mode. This was caused by tl
4	F.C-P	2	RP	R	13	Apollo bridge 2 tripped on FASOF due to command unit failure. Songo bridge 4 intertripped.
5	F.V	6	RP	R	13	Songo bridge 6 tripped on FASOF due to the valve firing monitor operating on w/phase. Apollo bridg
6	F.V	3	RP	R	13	Songo bridge 3 tripped on FASOF due to valve firing monitor operating on r/phase. Apollo bridge 3 i
8	F.O	5	BP	M	100	Songo lost all bridges due to an unknown fault and is still under investigation.
10	F.AC-E	8	RP	R	39	Songo 220kV bus-coupler tripped on over-current. Under investigation.
12	F.V	4	RP	R	2	Apollo bridge 4 tripped on FASOF due to a fault on the R/phase valve tank. Songo bridge 4 inter-trip
13	F.C-P	7	P	M	61	Bridge 7 was switched in. Immediately Pole 1 went down to 0MW.
14	F.V	6	RP	M	15	Songo bridge 6 tripped on FASOF while swapping of bridges was in progress.
15	F.DC-E	2	RP	R	15	Apollo bridge 2 tripped on FASOF due to B/phase transformer tap changer over pressure. Songo br
17	F.V	8	RP	M	3	Apollo bridge 8 tripped on FASOF due to a fault on the R/phase valve tank. Songo bridge 2 inter-trip
19	F.TL		P	M	100	Line 1 protection operated due to line faults calculated at 41km from Pietersburg towards Songo. S
20	F.DC-E	6	RP	R	32	Songo bridge 6 tripped on FASOF after losing filters. Apollo bridge 2 inter-tripped.
21	F.TL		RP	M	100	Line 1 protection operated due to line faults calculated at 41km from Pietersburg towards Songo.
23	F.TL		P	R	100	Line 1 protection operated due to line faults calculated at 41km from Pietersburg towards Songo.
25	F.V	6	RP	R	4	Songo bridge 6 tripped on FASOF due to valve tank faults. Apollo bridge 4 inter-tripped.
27	F.C-P	8	RP	R	2	Songo bridge 8 tripped due to cooling system problems. Apollo bridge 4 inter-tripped.
28	F.V	4	RP	M	28	Songo bridge 4 tripped due due to valve tank fault on the red phase. Apollo bridge 2 inter-tripped.
31	F.V	5	RP	R	1	Songo bridge 5 tripped on FASOF due to valve firing monitor. Apollo bridge 5 inter-tripped.
35	F.DC-E		P	M	57	Pole 2 tripped due to a fault at Apollo.
103	F.V	7	RP	R	3	Apollo bridge 7 tripped on FASOF due to "D" group alarm blue phase valve tank fault. Songo bridge
106	F.V	5	RP	R	35	Songo bridge 5 switched out on DESK-NOSOF due to air leak. Bridge 3 was switched in.
116	F.TL	6	RP	R	5	HVDC Line 2 protection operated. Distance recorder located the fault 220km from Petersburg to So
123	F.V	4	RP	M	26	Apollo bridge 4 switched out to reset Idref=0.4. Songo bridge 4 inter-tripped.
124	F.C-P	4	C	M	100	Pole 2 Idref = 0.4 from Apollo to Songo. Songo registering 0.3 which means current difference at tw
126	F.V	1	RP	M	28	Apollo bridge 1 tripped due to valve cooling fault caused by fans which were off. Songo bridge 3 int
127	F.V	4	RP	S	3	Apollo bridge 4 tripped due to blue phase valve tank fault. Songo bridge 4 inter-tripped.
131	F.TL		RP	M	16	Line 2 protection operated. The recorder located the fault 65,3km from Apollo between towers 164 -
138	F.V	6	RP	R	3	Songo brigde 6 FASOF,White phase
139	F.TL		RP	R	16	Line 2 protection operated. The recorder located the fault 193.32km from Songo. Songo bridge 6 wa
140	F.TL		P	R	30	Line 2 protection operated. The recorder located the fault 234km from Songo. Songo bridge 2 was s
145	F.AC-E	6	P	R	30	Apollo bridge 8 UPS faulted and tripped. Bridge 6 UPS also tripped since it is inter-linked to bridge
151	F.V	7	RP	M	37	Apollo bridge 7 tripped due to intermittent group "B" alarm. Songo bridge 3 inter-tripped.
155	F.DC-E		RP	M	100	Apollo filter 1 and 2 tripped on 5th and 7th harmonic over-load. At 11h53 Filter 2 tripped on closin

Record: 1 of 59
OUTAGE REFERENCE NUMBER

Figure 3.8 The Datasheet View of the Query called QryTABLE2F2002

The other five queries have similar properties. Queries allow the programmer to link and filter fields from different tables and other queries. Figure 3.7 and Figure 3.8 on the next page shows the Design View as well as the Datasheet View of the same query called QryTABLE2F2002.

3.7 Reports

The final object is the Report, which is used for presenting information and results in a format required by the programmer. In this context, the reports are used as the final presentation that is used in the database. They are directly linked to the buttons on the Main Menu of the database. The tables are listed in Figure 3.9. These are: the Outage Log Form Report, plus six other Reports which are associated with the Cigré tables.

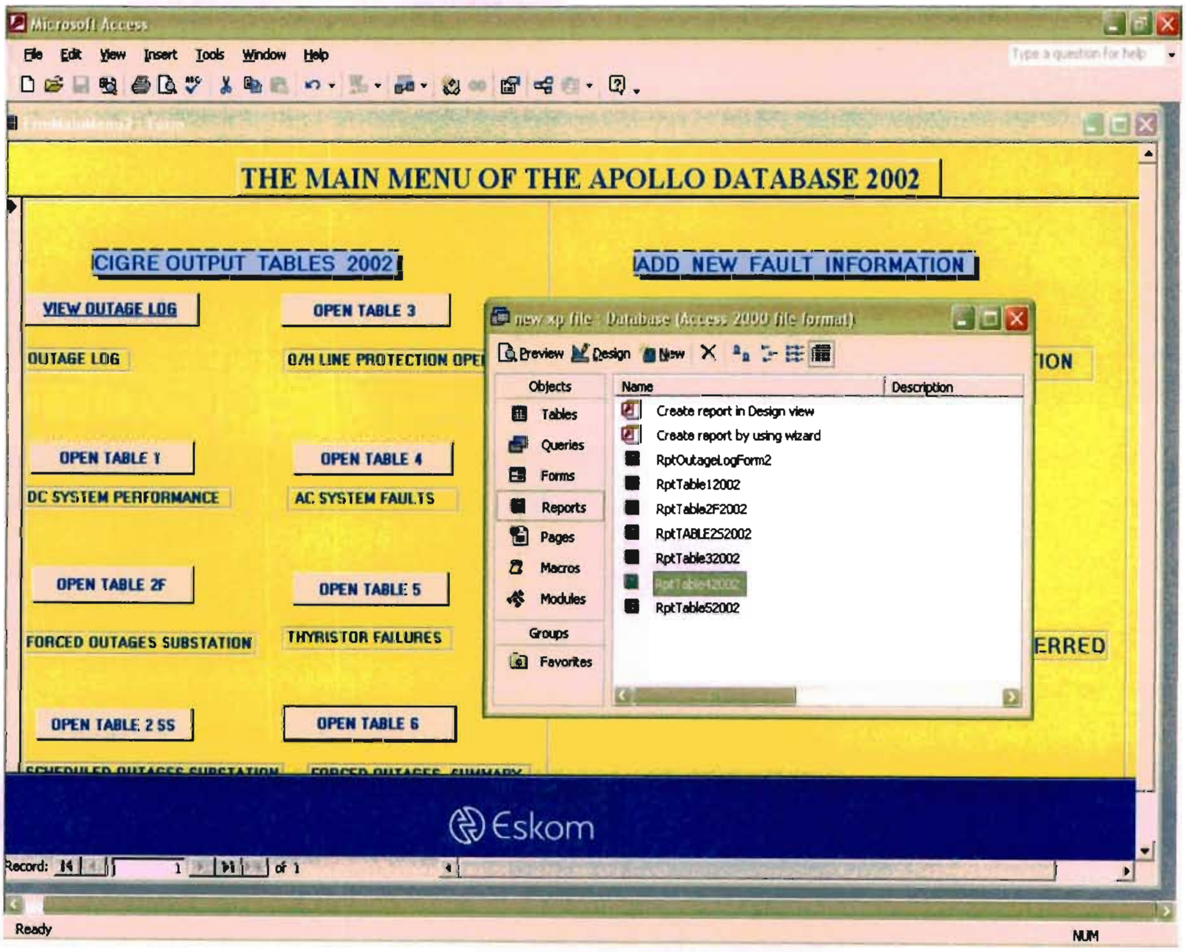
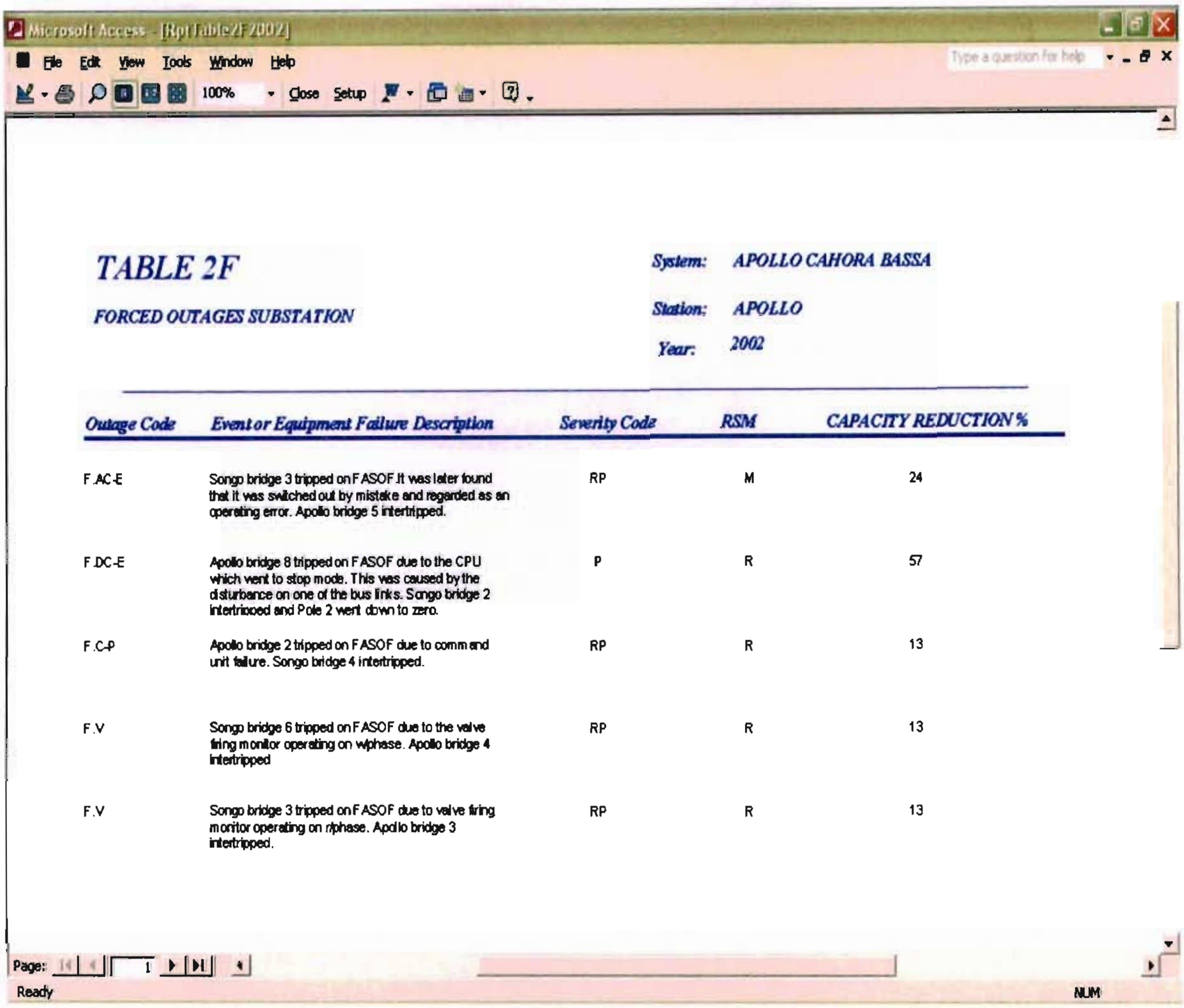


Figure 3.9 Main Menu Showing The Report Object Window.

When the user selects the "OPEN TABLE 2F" button, the screen in Figure 3.10 appears. The report is designed to resemble the format of Table 2F in the Cigré protocol.



Outage Code	Event or Equipment Failure Description	Severity Code	RSM	CAPACITY REDUCTION %
F.AC-E	Songo bridge 3 tripped on FASOF.It was later found that it was switched out by mistake and regarded as an operating error. Apollo bridge 5 intertripped.	RP	M	24
F.DC-E	Apollo bridge 8 tripped on FASOF due to the CPU which went to stop mode. This was caused by the disturbance on one of the bus links. Songo bridge 2 intertripped and Pole 2 went down to zero.	P	R	57
F.C-P	Apollo bridge 2 tripped on FASOF due to command unit failure. Songo bridge 4 intertripped.	RP	R	13
F.V	Songo bridge 6 tripped on FASOF due to the valve firing monitor operating on w/phase. Apollo bridge 4 intertripped	RP	R	13
F.V	Songo bridge 3 tripped on FASOF due to valve firing monitor operating on r/phase. Apollo bridge 3 intertripped.	RP	R	13

Figure 3.10 The Table2F Report.

The Design View as well as the Form View are similar for Reports. There are five forms that are used. Four of these represent the four input steps of the database. Theses are discussed in the next chapter. The fifth table is the Main Menu form. The Main Menu is the first window that opens when the database is activated.

CHAPTER 4

DATA POPULATION

The steps the user takes to populate data into the database are explained in detail in this chapter. All that is required of the user is a basic understanding of the workings of Microsoft® Windows software. The assessment results are used to compare the Cahora Bassa HVDC scheme to similar systems. The different options available to the user and definitions are explored. At the end the user understands each step and all the categories of information that is required to populate the database accurately.

4.1 SOURCE OF INFORMATION

The Daily Log Record from the Apollo Converter Station Control Room is the main source of information. It is used to capture all the events that happen on the HVDC system. The logged data includes:

- Time and date of the fault.
- Current, voltage and polarity.
- Power transmitted and power lost as well as frequency.
- Busbar voltage and reactive power.

Furthermore there is information on the list of equipment as demonstrated on Figure 4.1. All the active equipment is selected from the given check boxes. The listed equipment consists of:

- Filter 1 and 2
- AC Capacitors
- Bridges on both converter stations.
- And the generators.

On the right hand side of the Daily Log Record is a remarks section. In this section abbreviations are used. In the earlier work these are referred to as switching off programs. There are four switch-off programs and four other abbreviations. [12]

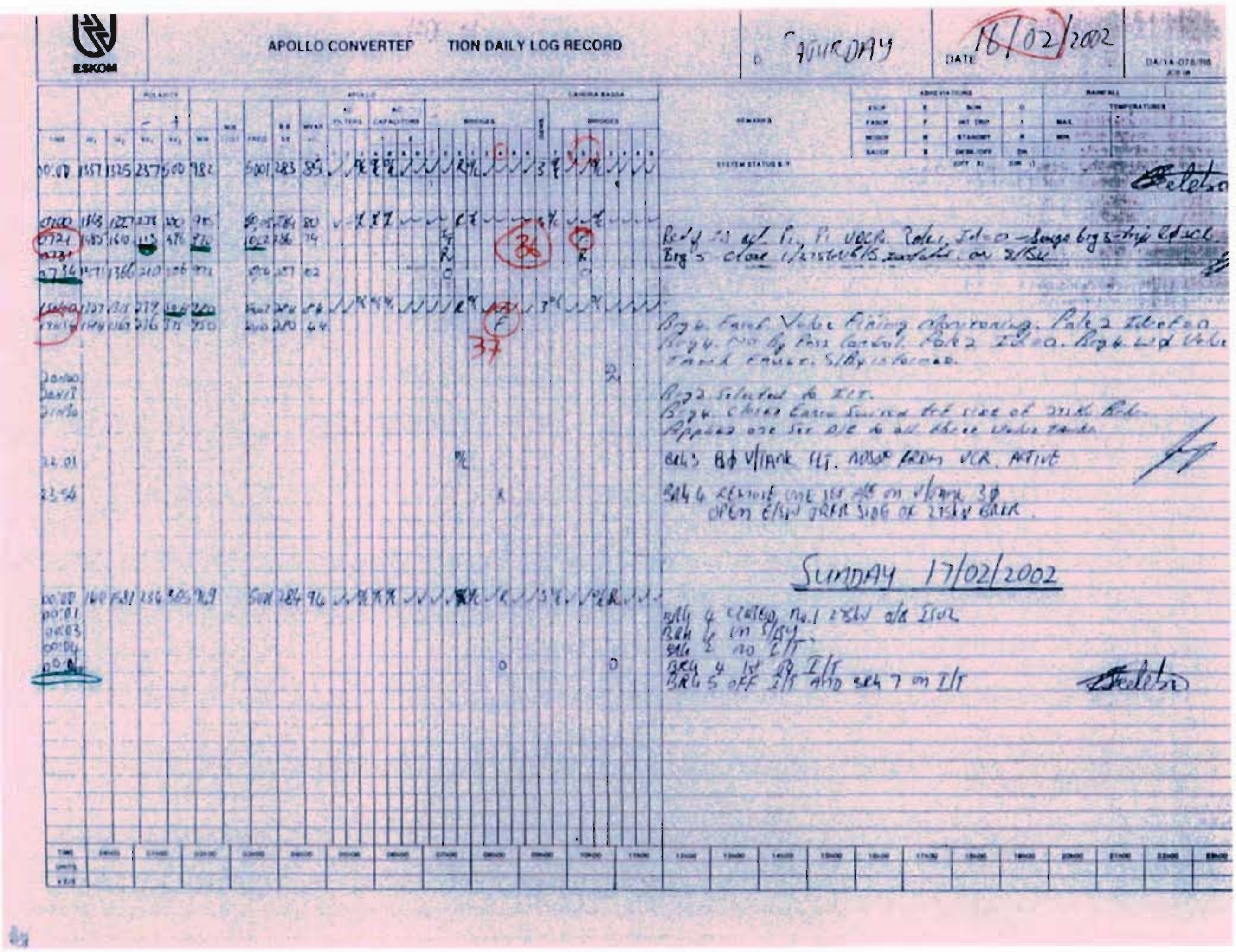


Figure 4.1: The Daily Log Record of Apollo Converter Station

Table 4.1.The Abbreviations Used in the Daily Log Record [12]

Abbreviation	Meaning	Abbreviation	Meaning
O	Switch On	E	ESOF
I	Inter-trip	F	FASOF
R	Standby	N	NOSOF
DN	Desk switch off	S	SACOF

4.1.1 Switch Off Programs

a. NOSOF [N]

This is Normal Switch Off. The program follows the sequence below:

Power reduced via Master Power Controller within 30 seconds.

Control angle changed to 90° within 10seconds.

Single phase by-pass control initiated.

AC breaker tripped.

Three phase by-pass control initiated.

By-pass breaker and isolator closed.

Polarity isolators opened.

Earth applied [12]

b. FASOF [F]

This is Fast Switch Off. It is initiated by protective devices other than those involving the over-current diverters. The program follows the following sequence:

The control angle is switched to 90°

Then follows the sequence in (a) above [12]

c. ESOF [E]

This is Emergency Switch Off. It is initiated after closure of over-current diverters in the case of an internal bridge short circuit. For an example when diverters close to protect the valves. When there is simultaneous initiation of tripping and closing pulses. Pulses going to the AC breaker, by-pass switch and isolator. Then the sequence from (a) above is followed. [12]

d. SACOF [S]

This is the Safety Switch Off. This serves as back-up to the switch off programs. It is programmed as follows:

Simultaneous initiation of current reference to zero.

Single phase by-pass

AC breaker trip and by-pass breaker and isolator close. [12]

4.2 DATA POPULATION PROCESS

The process of populating data into the database has been made easy by using colour and detailed descriptions. The Main Menu of the database shows the four steps to record a fault in the database, see figure 3.1.

4.2.1 Step One

When the user clicks on the "Add record" button on the Main Menu as seen on Figure 3.1, The Step 1 screen appears as depicted in Figure 4.2.

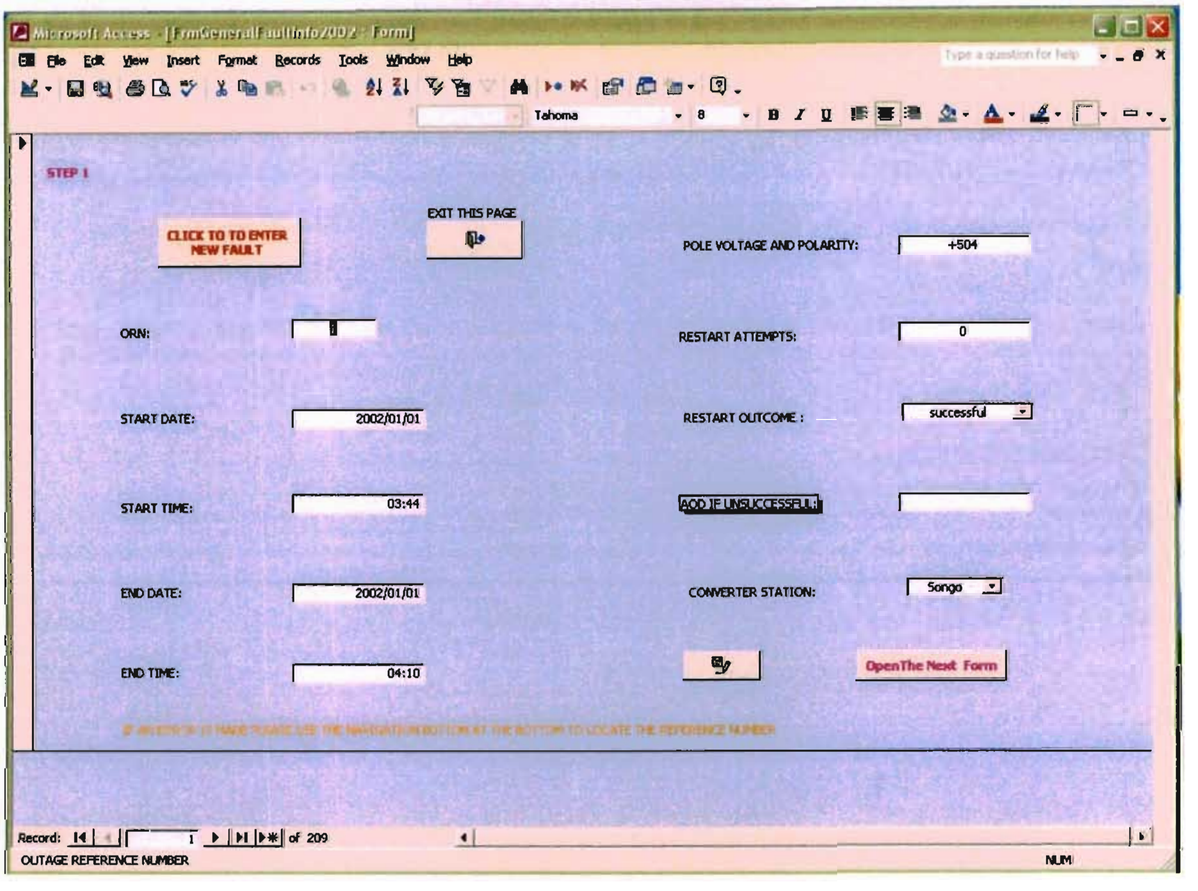


Figure 4.2: The first step of fault recording.

To aid the user in the data populating process each Step Number is displayed on the top left corner of the screen. **Directly** below the Step Number is a button called "Click To Enter New Fault", that initiates the process of entering new fault details. All the placeholders become blank and ready for new information to be entered, see Figure 4.3 on the next page. The following discussion is based on the screen displayed in figure 4.3. The first input is the fault number called ORN (Outage Reference Number). At the bottom of the screen there are two areas called Record area and the Description area. The description area gives details about the placeholder where the curser is. In Figure 4.3 the curser is on the ORN placeholder and the description area reads "OUTAGE REFERENCE NUMBER". The number displayed on the Records area will always be the same as the ORN number. On this same area the total number of records is displayed. There is a new record number 210 of a total 210 records in the database.

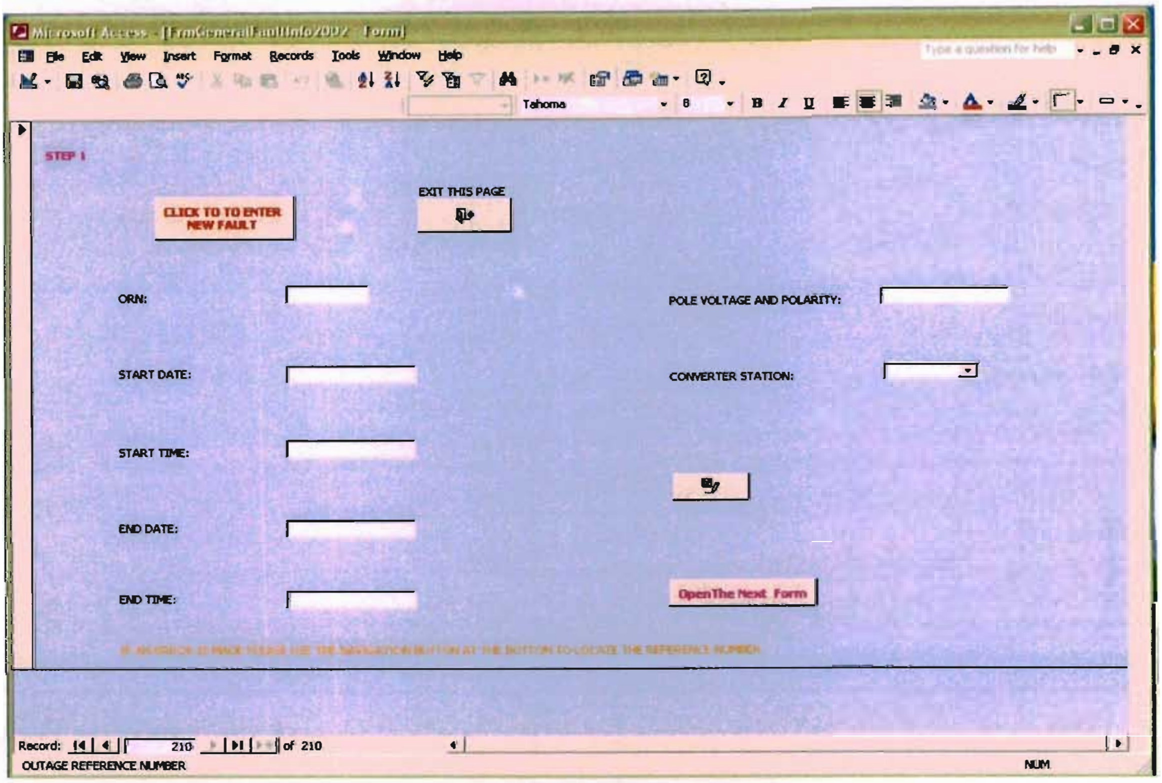


Figure 4.3: The Effects of clicking the New Fault Button.

After entering the number 210 on the ORN placeholder the user needs to press the Enter key. The next four placeholders have input masks that guide the user on the format of the dates and time placeholders. For details consult Appendix A. For these four placeholders there are associated details displayed on the description area.

The next placeholder is the Pole Voltage and Polarity of the system before the fault occurred. This placeholder is filled in manually. The next placeholder is the Converter Station placeholder, which is used to select the station where the fault occurred. It consists of a drop down menu that has two options Apollo or Songo. The next button is the Save button that saves the changes made to the database. The last button is the Next Step button which takes the user to step two. At any stage during the process of populating data the user can exit the page using the Exit button on the top right hand side of the screen.

Figure 4.4 shows a completed Step 1 where all the placeholders are filled up. Displayed is Record number 186 of 209 records. The fault was caused by an incident at Apollo Converter Station on the 27 November 2002. The Time at which the fault occurred was 18:45 and the voltage was +358kV. The fault was cleared on the same day at 18:51.

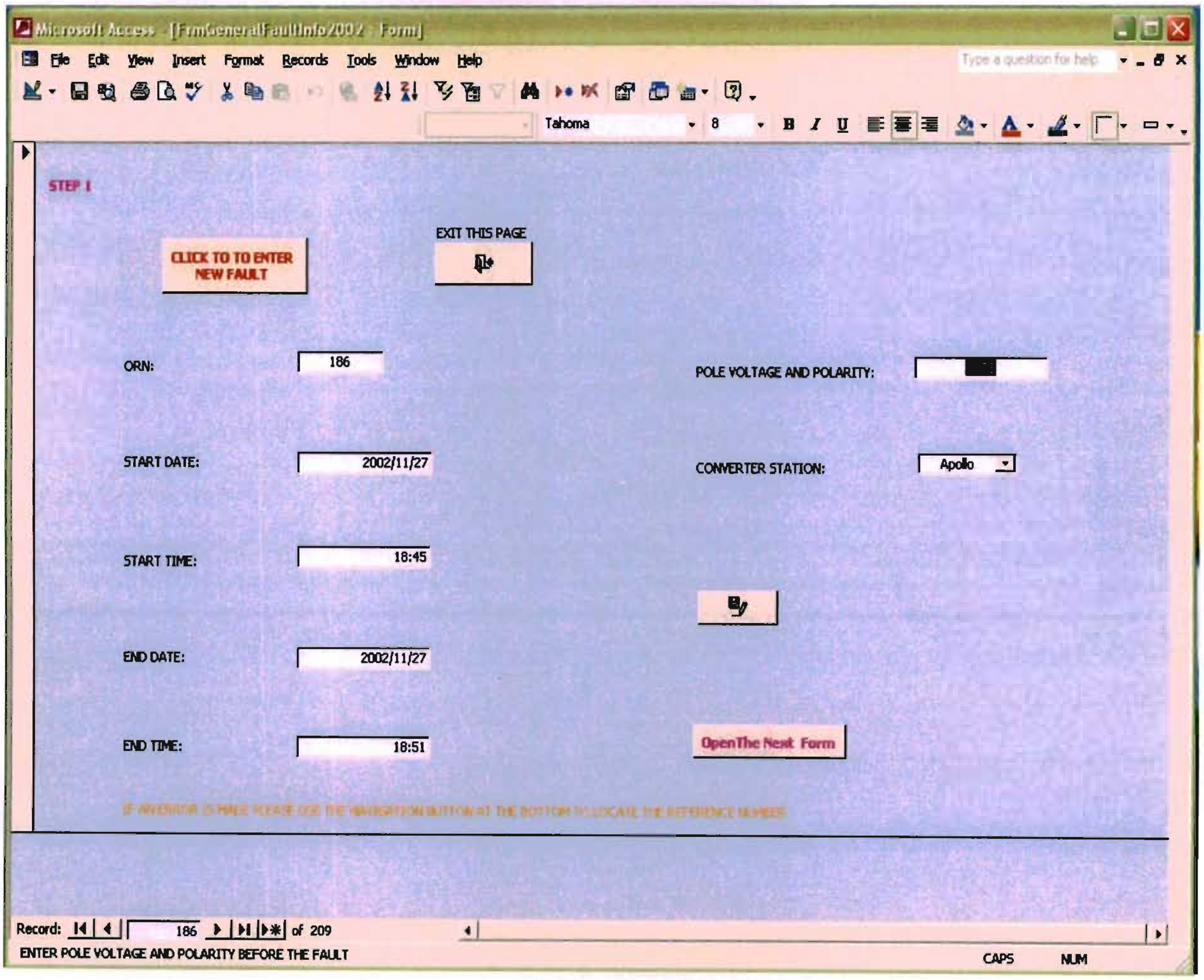


Figure 4.4: A Completed Step1.

The details captured in Step 1 get analysed in Microsoft® Excel and the results are imported by Microsoft® Access for completing the Cigré output table called Table1F. The imported table is called TblForTable1Calculation. This naming convention is used throughout the database. The first three letters indicate the type of object used.

4.2.2 Step Two

The first noticeable feature of Step 2 is the different screen colour. In addition there are different colours that are used to guide the user in filling the relevant placeholders, see Figure 4.5. This step focuses on the classification of faults, the general details of faults were recorded in Step one. The ORN placeholder contains the same number in all the four steps as in Step one. As before the record number at the button is the same as the faults number, ORN. At the top left corner is the step number again written in the colour pink.

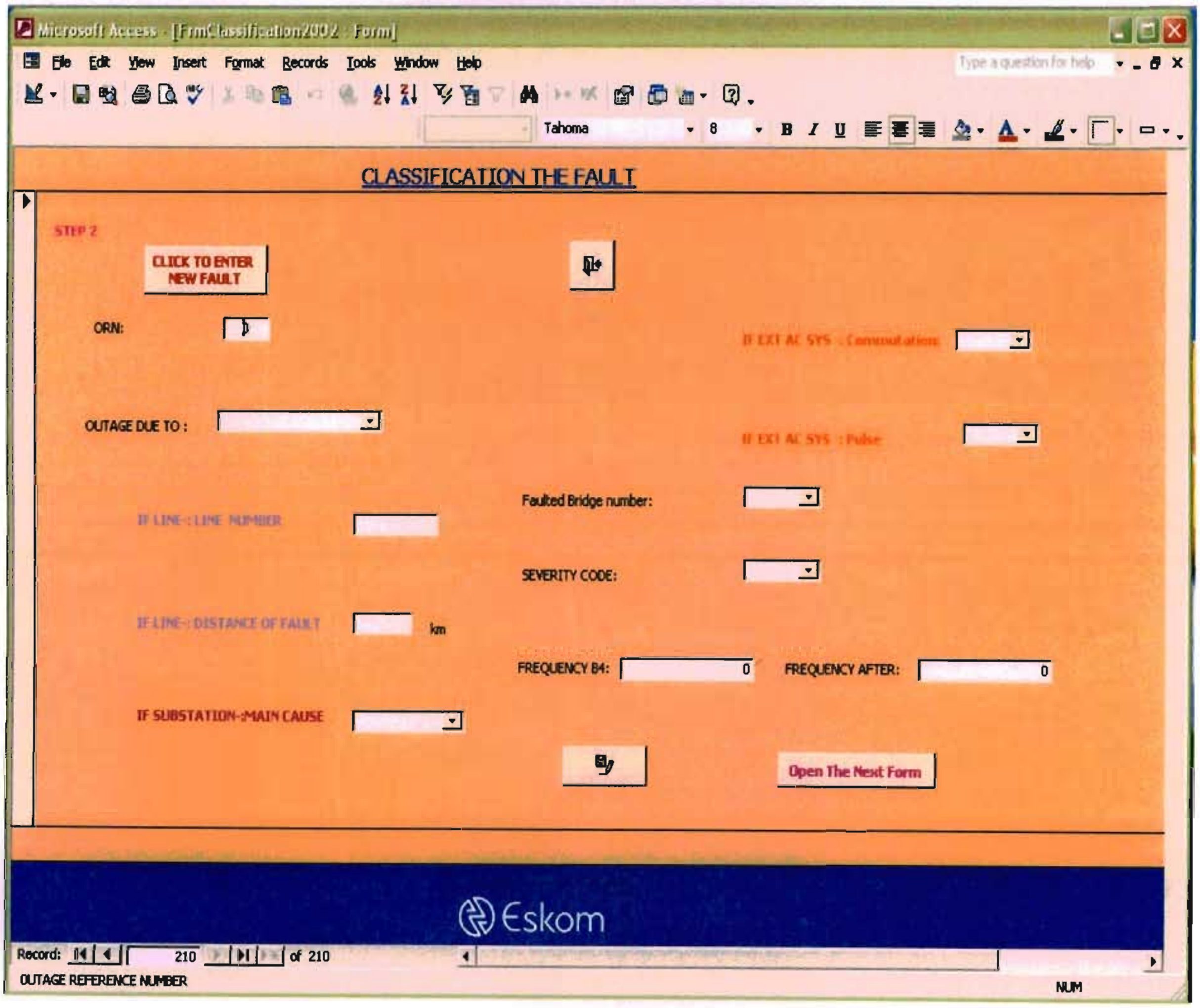


Figure 4.5: Step Two New Record Screen

The fault the user records has a cause. This information must be recorded on the Outage Due To placeholder, see Figure 4.6 for the available options.

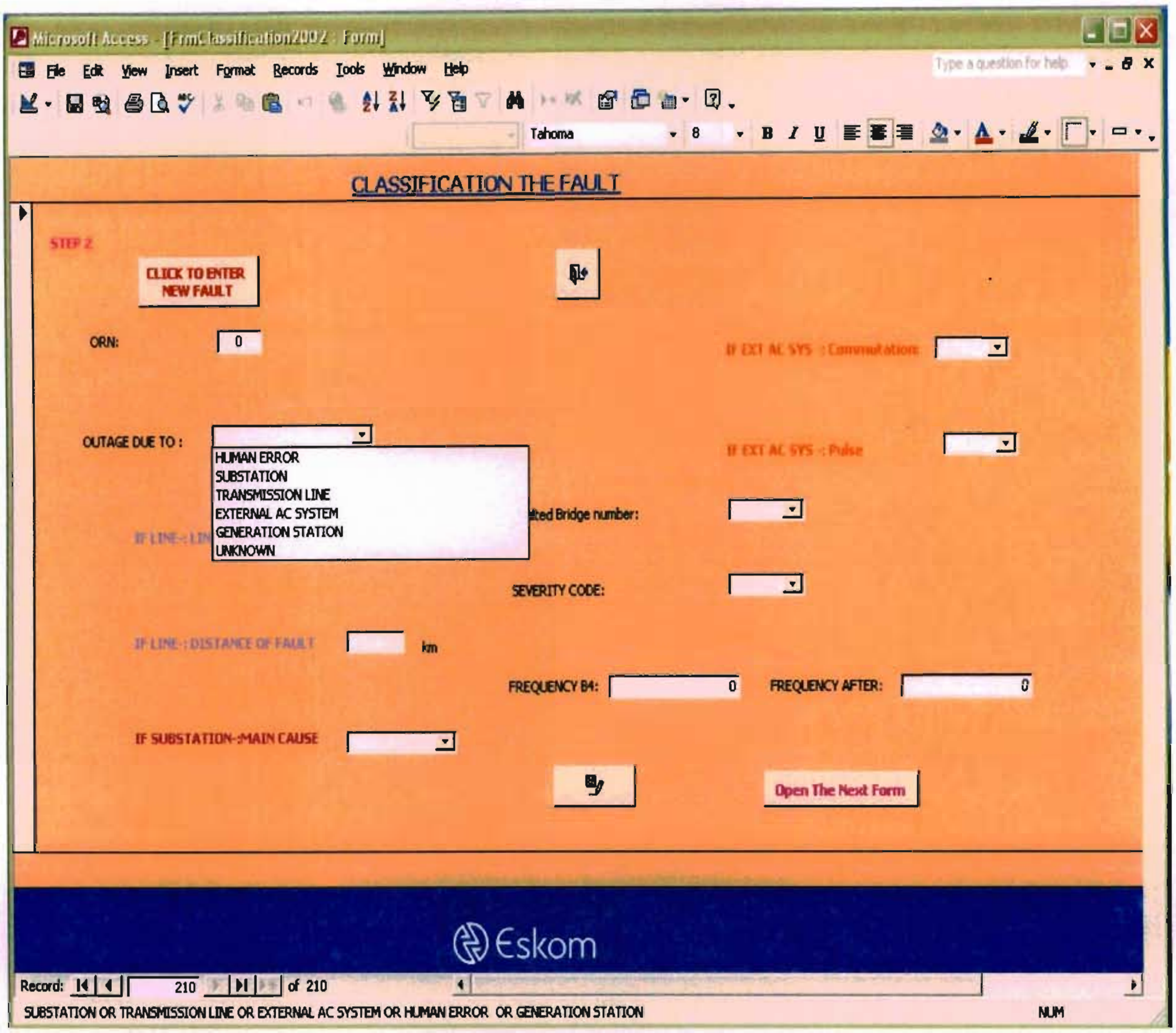


Figure 4.6: Step Two Window Showing The Outage Options

The user interprets the control Daily Log Record to get the details of the fault. The "Due-To" information is then filled up. There are six classifications of forced outages that are used

4.2.2.1 Human Errors

This is for all the faults that the Control Room Operators classify as human errors and state it in the Daily Log Record. This category is an instance of category 4.2.2.6 the (Unknown/Other). It is recorded separately to eliminate errors when populating data into the database.

4.2.2.2 Substation Outages

In each of these, the number of outages and the amount of time for which the equipment was out is recorded. This classification is very precise, making it easy to record the specific outage in the correct field.

a) AC and Auxiliary EquipmentAC-E

This category includes all converter transformers, line side and tertiary connected A.C plant and the A.C plant in the HVDC substation.

Included also is the converter transformer up to the external connection clamp on the valve side of the bushings, as well as the conventional A.C substation auxiliary equipment. Some of the equipment in this category include [9]:

- A.C Switchgear (Line Side and Auxiliary Power Switchgear)
- A.C Harmonic Filters
- Reactive Compensation (only if this it is necessary for the operation of the substation)
- Transformers (both the converter and the auxiliary transformers)
- Motors (including the auxiliary motors used to drive cooling fans and pumps)
- Protection on
  - Transformers
  - A.C Bus
  - Filters
  - Motors
  - Current Transformers
  - Voltage Transformers
  - And other auxiliaries
- Mechanical Plant such as
  - Heat Exchangers
  - Cooling Towers for valve cooling and fans
- Surge Arresters on
  - A.C Bus
  - A.C Switchgear
  - Filters
  - And line side of Transformers

b) Valves V

The valves include the entire operative array forming an arm, or part of an arm of the converter bridge. The valve includes all the auxiliaries and components integral to the valve and forming part of the operative array. [9]

c) Control and Protection C-P

This category is for equipment used for control of the HVDC system. It is also for the control, monitoring and protection of each HVDC substation excluding specifically the conventional substation. Included in this category is all the equipment that is provided for the coding of control and indication information that is sent over the telecommunication circuit and the circuit itself is included. [9]

Excluded are disconnectors and circuit breakers as well as the transformer tap changers that may actually perform the control or protection action. However, control equipment such as the current and voltage measuring transducers are included since they are directly connected to the primary system. [9]

d) Other Primary DC Equipment DC-E

This category caters for all the equipment that is in the substation and does not fall in the three categories above. Some of the equipment in this category includes;[9]

- D.C Reactor
- D.C Switchgear
    - Disconnectors
    - Earth switches
    - Overcurrent Diverters
- Valve side Surge Arresters
- D.C reactor surge Arresters
- D.C Filters
- Earth Electrode
- Earth Electrode lines
- D.C line Arresters (even at the point far from the substation).

4.2.2.3 Transmission Line TL

This category is for all the transmission line outages and excludes line protection operations. For this group of faults the two purple placeholders are completed. They are the Line Number and Line Distance placeholders. [9]

4.2.2.4. External AC System

This category is for all the faults in the ac network external to the converter. Examples would include ac network instability, ac overvoltage in excess of the convertor protective rating, short circuit level lower than the minimum design level, loss of ac outlet line(s) or loss of generation. In this database loss of generation has its own category, thus removed from this one. [9]

4.2.2.5 Generation Station

The Generation Station Category is an instance of External AC System category mentioned earlier. This is for all the Cahora Bassa power station faults. For the purpose of easy analysis this category was placed separately.

4.2.2.6 Unknown / Other O

This is for all the unknown causes as well as those due to human errors. If, after an outage due to an event in another category, the outage duration is extended due to human error in maintenance or operation, the consequential extension in outage time is charged to this category. [9]

4.2.3 Step Three

Further details are recorded in this step. The restoration method as well as the lost energy is recorded here. After filling in the fault number ORN, the RSM placeholder is filled in. Figure 4.7 shows the Step 3 screen. The curser is on the RSM placeholder, the description area gives details of the letters RSM. In addition the drop down menu consists of a second column which also describes the abbreviations.

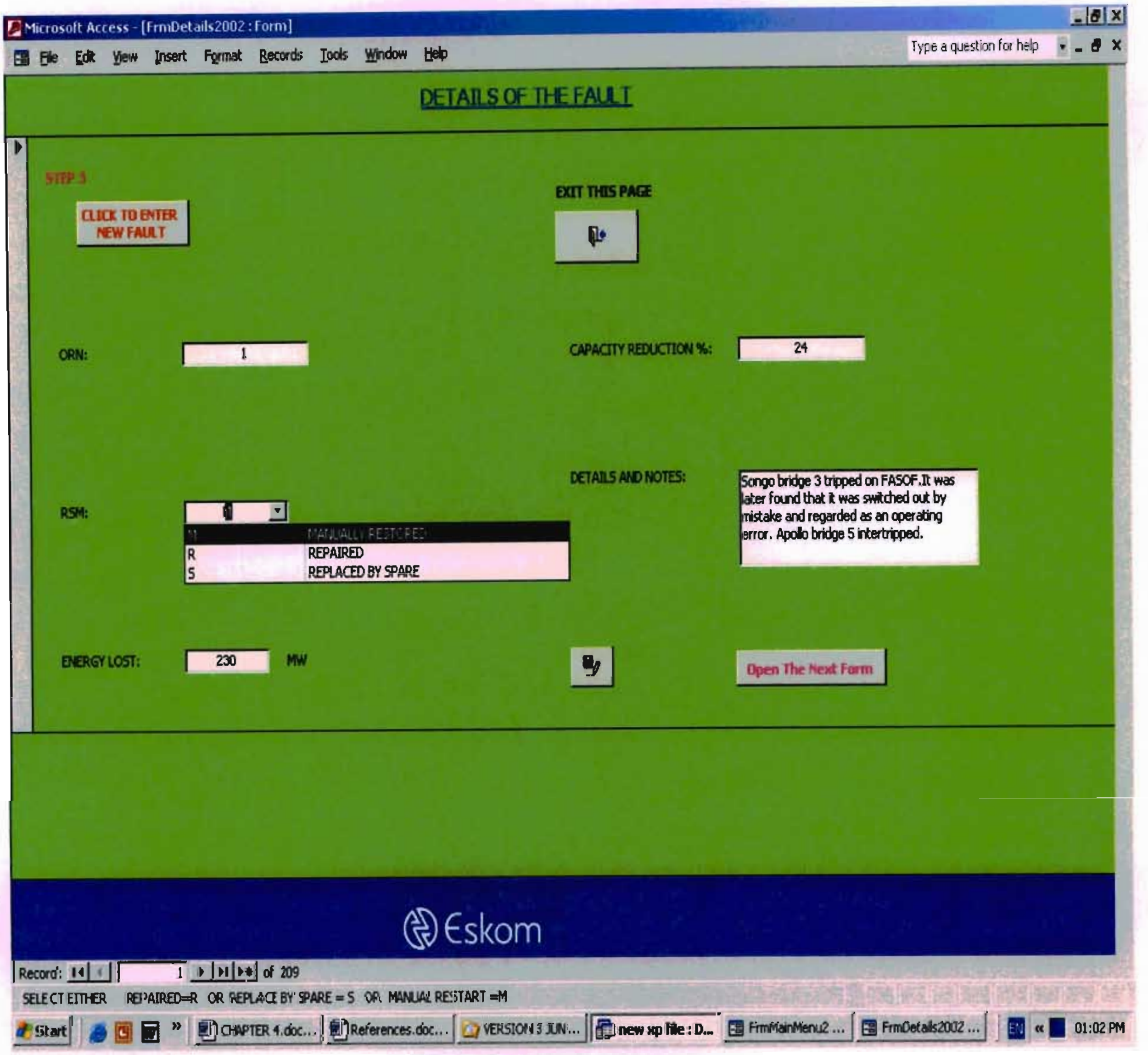


Figure 4.7: Step Three Window

The last placeholder stores the detailed notes on events concerning the fault. For example in Figure 4.7 the following details are displayed: "Songo Bridge 3 tripped on FASOF. It was later found that it was switched out by mistake and regarded as an operating error. Apollo Bridge 5 intertripped."

4.2.4 Step Four

This step requires the completion of the following three placeholders: Month, the total number of Hours in that month (PH) and Total Energy imported during that month (E_{import}), as shown in Figure 4.8. There is a save button to save all the entries made. Finally the user clicks on the Exit button to go back to the main menu. This completes the process of populating the particulars of each fault into the database.

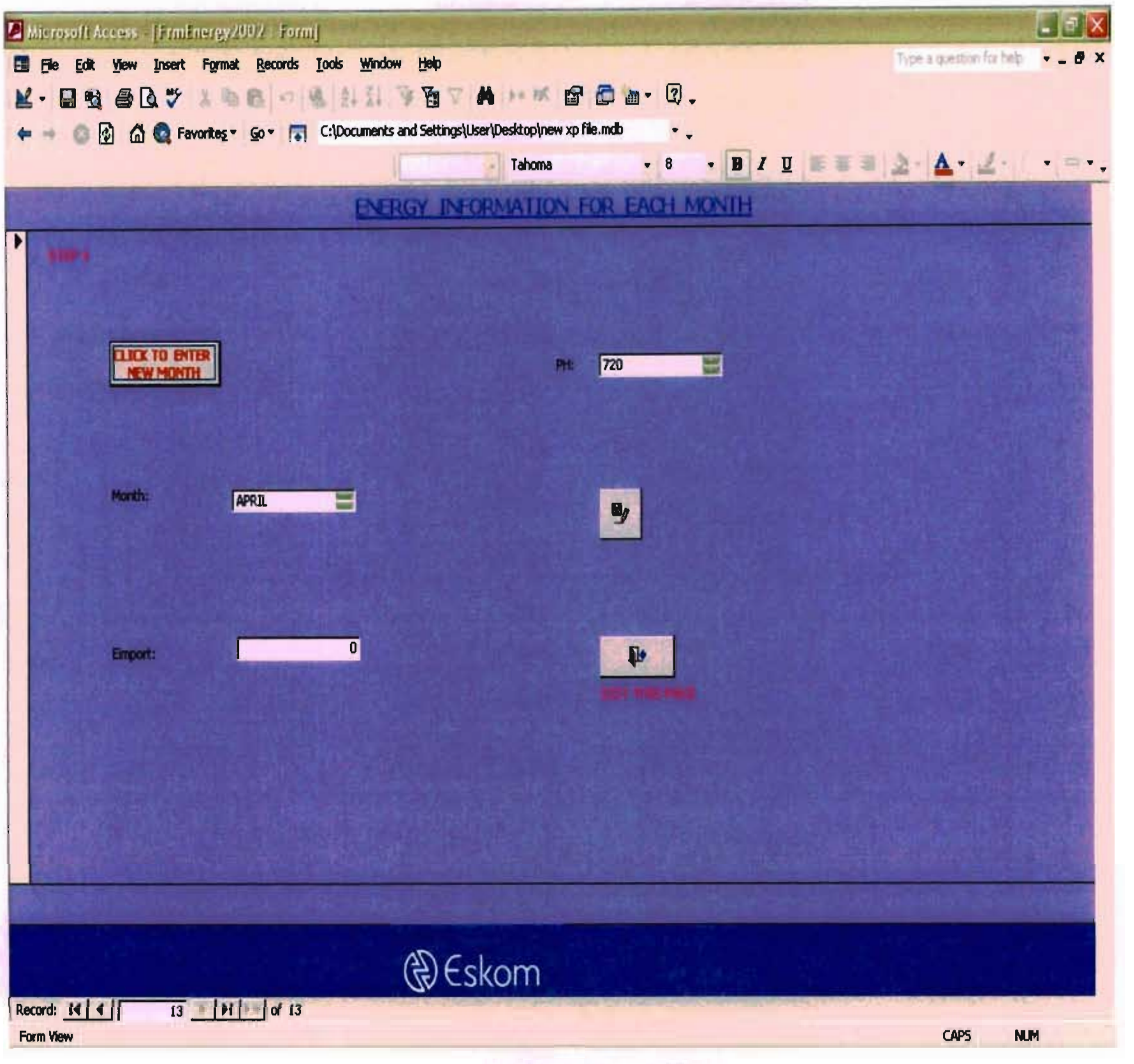


Figure 4.8: Step Four Window

4.3 CONCLUSION

All the four steps on database population are comprehensively covered in this chapter. The user is able to follow the process and each logged fault will be recorded accordingly. The details are in separate tables in different row and columns, this gives a lot of flexibility in the data analysis.

CHAPTER 5

COMPARISON WITH OTHER SYSTEMS

5.1 INTRODUCTION

The Working Group 14 regularly issues a publication called "A Survey of the Reliability of HVDC Systems Throughout The World". These publications as well as the "Compendium of HVDC Schemes Throughout the World" are also referred to in this chapter. The criterion for comparing similarities includes voltage level, transmission line distance as well as the power transmission capability.

5.2 SIMILARITY CRITERION

In this study, systems considered to be similar to Cahora Bassa are those which have a comparable voltage level, power transmission capability and transmission line distance. Naturally they will have to be point to point schemes that make use of thyristor valve technology. The age of the systems was not considered as a criterion because there are a few HVDC schemes in the world to consider for this exercise. Eight systems which were considered to be similar to Cahora Bassa are listed in Table 5.1

Table 5.1 Criterion For Similarity [13]

	Voltage Level [kV]	Transmission line Distance [km]	Power Transmission Capability [MW]
CAHORA BASSA	±533	1414	1920
CU	±400	701	1000
INGA SHABA	±500	1700	560
PAC INTERTIE	±500	1362	2000
INTERMOUNTAIN	±500	784	1920
ITAIPU II	±600	805	3150
HYDRO QUEBEC	±450	1500	2000
RIHAND DELHI	±500	910	1500
NELSON RIVER BIPOLAR 2	±500	930	1920

The comparable voltage level was considered to be greater or equal to four hundred kilovolts. For the comparable transmission line distance, lengths of seven hundred kilometres and greater were considered. Five hundred megawatts of Power Transmission capability was the minimum criteria used.

5.2.1 COMPARISON INDICES

The following have been used as comparison indices:

- Energy Availability percentage
- Energy Utilisation percentage
- The number of Forced outages
- Equivalent outage hours

The Cahora Bassa scheme is compared to the Nelson River bipolar 2(CDN) for the period 1979 to 1980. The details are listed in the document called "Survey of the Reliability of HVDC Systems throughout the world 1979 to 1980". See Table 5.1 for a list of similar systems. [14]

5.3 ENERGY AVAILABILITY AND UTILISATION

In this section the Energy Availability and Utilisation data of all the systems that were identified as similar are analysed. Five periods over the past years are put together and compared to the available Apollo Converter Station data. Cahora Bassa submitted performance data for the 1979 to 1980 Cigré reporting period.

5.3.1 Energy Availability and Utilisation 1979 to 1980

Table 5.2 compares the two schemes for the years 1979 to 1980. The Cahora Bassa scheme had a higher Energy Availability percentage. This means that 96.8 percent and 92.9 percent of energy could have been transmitted over the Cahora Bassa HVDC scheme except for limitations of capacity due to forced and scheduled outages of the converter station equipment and transmission lines [14].

Table 5.2 Comparing Cahora Bassa to Nelson River [14]

SCHEME NAME	Energy Availability [%]		Energy Utilisation [%]	
	1979	**1980**	**1979**	**1980**
CAHORA BASSA	96.8	92.9	80.5	62.5
NELSON RIVER BIPOLAR 2	68.4	91.5	35.3	30.8

The highest Energy Availability percentage for Cahora Bassa and Nelson River Bipolar 2 was 96.8 and the lowest was 68.4 percent. The average Energy Availability percent was 87.4.

For the period 1979 to 1980 in Table 5.2 the Energy Utilization, which is a measure of the energy actually transmitted over the Cahora Bassa Scheme was at 80.5 percent and 62.5 percent. Generally HVDC schemes aim for a high Energy Utilization, however schemes which are mainly used for standby capacity will have a low Energy Utilisation percentage. The average Utilisation value is 52.2 percent. [14]

5.3.2 Energy Availability and Utilisation 1995 to 1996

There were twenty two Thyristor Valve system that submitted performance data to Cigré for the period 1995 to 1996. Only four systems listed in Table 6.3 met the similarity criteria. [15]

Table 5.3 Comparing Similar systems For the Period 1995 to 1996 [15]

SCHEME NAME	Energy Availability [%]		Energy Utilisation [%]	
	1995	1996	1995	1996
CU	96.8	96.9	70.1	71.1
ITAIPU II	97.4	98.7	68.2	73.4
RIHAND DELHI	-	93.7	-	64.2
NELSON RIVER BIPOLAR 2	96.6	94.0	63.8	77.7

The Energy Availability percentages for the four systems remain within the same range. The minimum value being 93.7 percent and the maximum is 98.7 percent. The average value was 96.31. These percentages are comparable to the previous period of 1979 to 1980. The maximum and minimum percentages were 96.8 and 68.4 respectively.

For the period 1995 to 1996 the Energy Utilization percentages are listed in Table 5.3 Energy Utilisation is a measure of the energy actually transmitted over the system in a given period. For the similar systems in Table 5.3 the lowest value was 63.8 percent and the highest value was 77.7 percent. [15]

The average Energy Utilisation for these systems is 69.79.

5.3.3 Energy Availability and Utilisation 1997 to 1998

Energy Availability percentages of the four systems remain within the same range. The minimum value is 91.4 percent and the maximum is 98.3 percent. The average value is 96.05. These percentages are comparable to the previous period of 1995 to 1996. The maximum and minimum percentages were 98.7 and 93.7 respectively.

For the period 1997 to 1998 the Energy Utilization percentages are listed in Table 5.4 Energy Utilisation is a measure of the energy actually transmitted over the system in a given period. For the similar systems in Table 5.4 the lowest value was 63.5 percent and the highest value was 80.1 percent. [16]

The average Energy Utilisation for these systems is 72.54.

Table 5.4 Comparing Similar systems For the Period 1997 to 1998 [16]

SCHEME NAME	Energy Availability [%]		Energy Utilisation [%]	
	1997	1998	1997	1998
CU	96.3	95.6	68.8	66.8
ITAIPU II	98.3	98.2	80.1	79.0
RIHAND DELHI	95.7	91.4	65.5	63.5
NELSON RIVER BIPOLAR 2	97.6	95.3	79.8	76.8

5.3.4 Energy Availability and Utilisation 1999 to 2000

Of the twenty three systems that submitted performance data to Cigré, for the period 1999 to 2000, only three listed in Table 5.4 meet the similarity criteria[17].

Table 5.5 Comparing Similar Systems in the Period 1999 to 2000 [17]

SCHEME NAME	Energy Availability [%]		Energy Utilisation [%]	
	1999	2000	1999	2000
CU	97	99.5	71.7	76.3
ITAIPU II	98	97.3	78	77.4
NELSON RIVER BIPOLAR 2	93.4	87.8	60.4	63.8

The lowest value was 87.8 percent and the highest was 99.5 percent. This is the highest value in all the periods considered for these similar systems. The average value was 95.45 percent. The combined average for the three periods considered is 95.97 percent.

Energy Utilization percent for the period 1999 to 2000 in Table 5.4 ranges from 60.4 to 78 percent. [17] The average value is 71.27 percent. The combined average value for all the three periods under consideration is 71.26 percent. These average values are almost equal.

5.3.5 Energy Availability and Utilisation 2001 to 2002

There are three systems in Table 5.5 that meet the similarity criteria from all the system that submitted performance data to Cigré for the period 2001 to 2002. The Apollo Converter Station values were taken from the Database discussed in this work. It must be noted that only the Apollo statistics are presented in this work, the Songo Converter Station statistics were not considered.

Table 5.6 Comparing Similar Systems in The Period 2001 to 2002 [18]

SCHEME NAME	Energy Availability [%]		Energy Utilisation [%]	
	2001	**2002**	**2001**	**2002**
CU	93.3	96.7	75.1	76.6
APOLLO		97.7		46.6
RIHAND DELHI	79.2	-	58.2	-
NELSON RIVER BIPOLAR 2	91.3	78.4	72.4	53.2

The highest Energy Availability value was 96.7 percent; the lowest value was 78.4 percent for the systems that submitted the performance data to Cigré for this period. [18]. The average value was 73.15 percent. The overall average value for all the four periods considered is 94.39. The Energy Availability of 97.7 percent calculated in this work for Apollo Converter Station is slightly higher than the average of the four years considered in this analysis, see Figure 5.1.

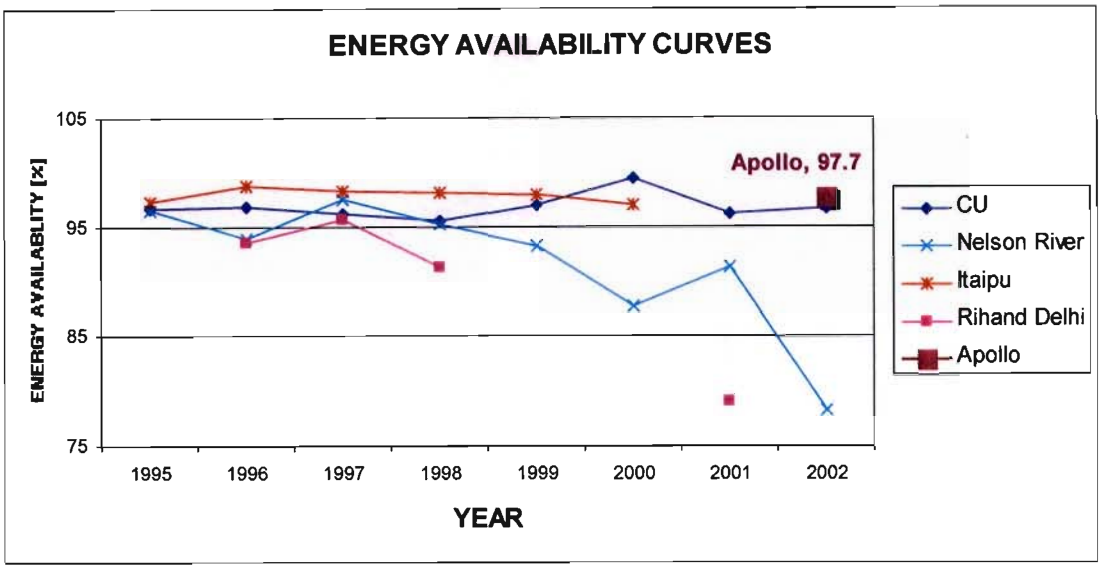


Figure 5.1 The Energy Availability curves of Similar Systems

For the period 2001 to 2002 the Energy Utilization percentages are listed in Table 5.5 Energy Utilisation is a measure of the energy actually transmitted over the system in a given period. For the similar systems in Table 5.5 the lowest value was 53.2 percent and the highest value was 76.6 percent. The average value is 55.92 percent. [18]

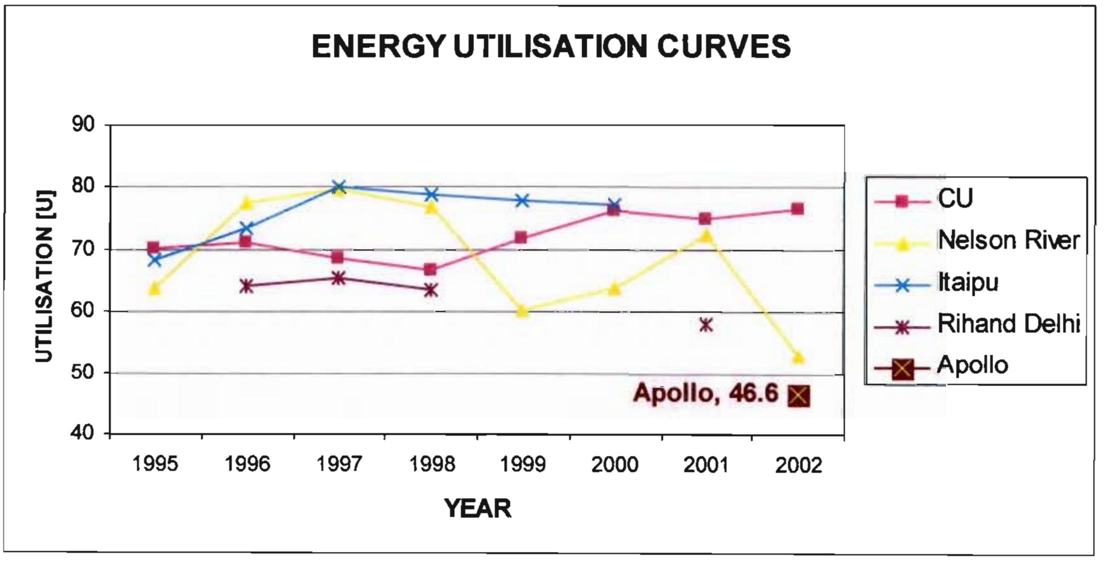


Figure 5.2 The Energy Utilisation curves of the Similar Systems

The overall average value for all the four periods considered is 70.46. The Energy Utilisation of 46.6 percent calculated in this work for Apollo Converter Station is the lowest value compared to the other systems, see Figure 5.2.

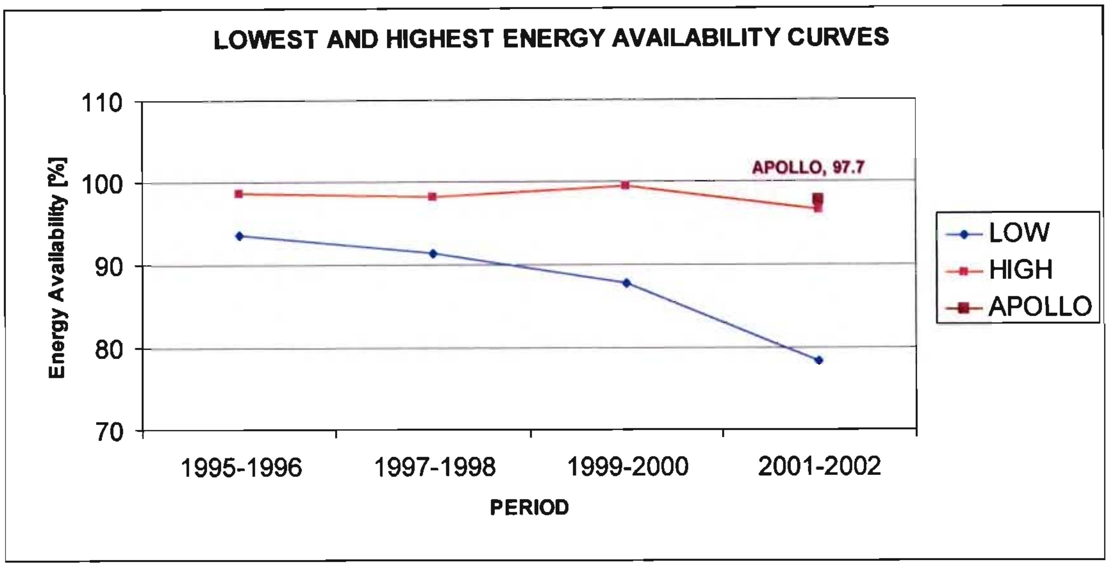


Figure 5.3 Lowest and Highest Energy Availability curves

Figures 5.3 and Figure 5.4 shows where Apollo Utilisation and Availability values are situated outside the boundaries of the Lowest and Highest Availability and Utilisation curves. This implies that in the year 2002, for Apollo Converter station 97.7% energy could have been transmitted over the Cahora Bassa HVDC scheme except for limitations of capacity due to forced and scheduled outages of the converter station equipment and transmission lines. This value is slightly greater than the highest value attained by similar reporting systems in that period.

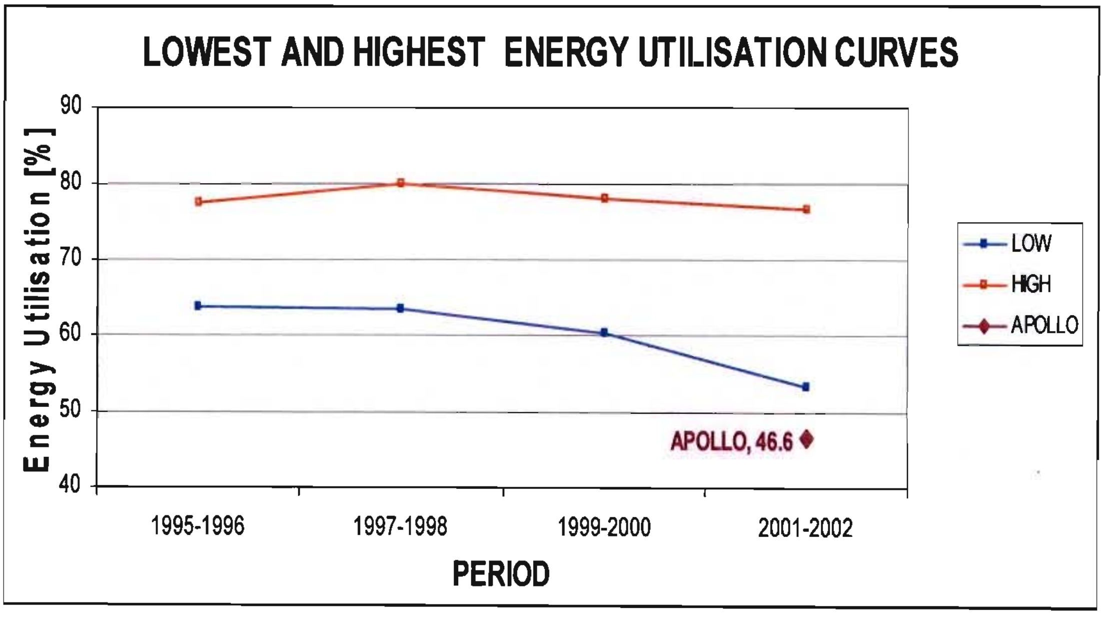


Figure 5.4 Lowest and Highest Energy Utilisation curves

Similarly the implications for Apollo is that the Energy Utilisation of 46.6% calculated for this period much lower than the lowest value of all the reporting schemes in that period. This is also means that 46.6% of the energy was actually transmitted over the scheme in the year 2002. There are a number of factors that influenced this figure; among them is the unavailability of one of the poles for extended period in the year.

5.4. Forced Outages and Equivalent Outage Hours

Equivalent forced outage hours (EFOH) is the sum of the actual forced outage hours after the outage duration has been adjusted for the percentage of reduction in capacity due to the outage.[15]

5.4.1 Forced Outages and Equivalent Outage Hours 1995 to 1996 [15]

Table 5.7 EFOH Data For Similar Systems in The Period 1995 to 1996

	NUMBER OF FO		EFOH	
	1995	1996	1995	1996
CU	17	12	11.2	11.4
ITAIPU BP1	7	8	4.6	19.8
ITAIPU BP2	14	10	42.5	7.7
NELSON RIVER BP2	62	49	54.8	229.9

In the 1995 to 1996 period the numbers of Forced Outages for these systems in Table 5.6 vary significantly. The lowest number of Forced Outages was seven from Itaipu BP1; the highest was Nelson River BP2 with 62. The lowest and highest Forced Outages correspond to 4.6 and 54.8 Equivalent Outage Hours. The highest Equivalent Outage Hours of 229.9 Hours for this period come from the 49 forced outages and not the 62 forced outages in the Nelson River BP2 1996 data.

5.4.2 Forced Outages and Equivalent Outage Hours 1997 to 1998 [16]

Table 5.8 EFOH Data For Similar Systems in The Period 1997 to 1998

	NUMBER OF FO		EFOH	
	1997	**1998**	**1997**	**1998**
CU	5	6	2.5	161.3
ITAIPU BP1	16	6	75.8	4.0
ITAIPU BP2	18	11	11.0	53.5
NELSON RIVER BP2	92	33	47.4	336.0
RIHAND DADRI	15	9	58.6	581.5

The numbers of Forced Outages for these systems in Table 5.7 also vary significantly. The lowest number of Forced Outages was five from CU in 1997; the highest was Nelson River BP2 with 92. The lowest and highest Forced Outages correspond to 2.5 and 47.4 Equivalent Outage Hours. The highest Equivalent Outage Hours of 581.5 Hours for this period come from the 9 forced outages and not the 92 forced outages in the Nelson River BP2 1997 data.

5.4.3 Forced Outages and Equivalent Outage Hours 1999 to 2000 [17]

Table 5.9 EFOH Data For Similar Systems in The Period 1999 to 2000

	NUMBER OF FO		EFOH	
	1999	**2000**	**1999**	**2000**
CU	5	7	3.3	13.1
ITAIPU BP1	7	9	19.3	4.2
ITAIPU BP2	19	6	62.4	4.1
NELSON RIVER BP2	33	53	208.4	884.5

The numbers of Forced Outages for these systems in Table 5.8 also vary significantly. The lowest number of Forced Outages was five from CU in 1999; the highest was Nelson River BP2 with 53. The lowest and highest Forced Outages correspond to 3.3 and 884.5 Equivalent Outage Hours.

5.4.4 Forced Outages and Equivalent Outage Hours 2001 to 2002 [18]

Table 5.10 EFOH Data For Similar Systems in The Period 2001 to 2002

	NUMBER OF FO		EFOH	
	2001	2002	2001	2002
CU	7	5	20.1	1.8
NELSON RIVER BP2	47	58	510.1	1614.7
RIHAND DADRI	21	-	1575.4	-

The numbers of Forced Outages for these systems in Table 5.9 also vary significantly. The lowest number of Forced Outages was five from CU in 2002; the highest was Nelson River BP2 with 58. The lowest and highest Forced Outages correspond to 1.8 and 1614.7 Equivalent Outage Hours.

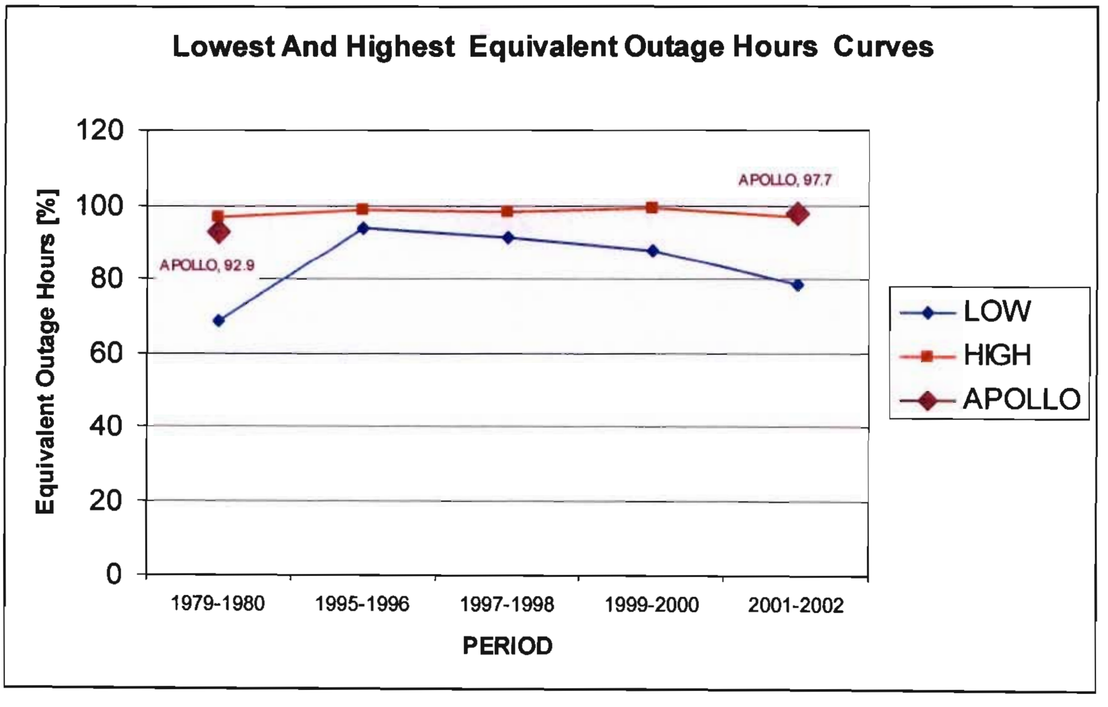


Figure 5.5 Lowest and Highest Equivalent Outage Hours curves

Figures 5.5 and Figure 5.6 shows where Apollo Forced Outages and Equivalent Outage Hours values are situated within the boundaries of the Lowest and Highest curves. CU scheme has had the lowest number of Forced Outages since the 1997 period.

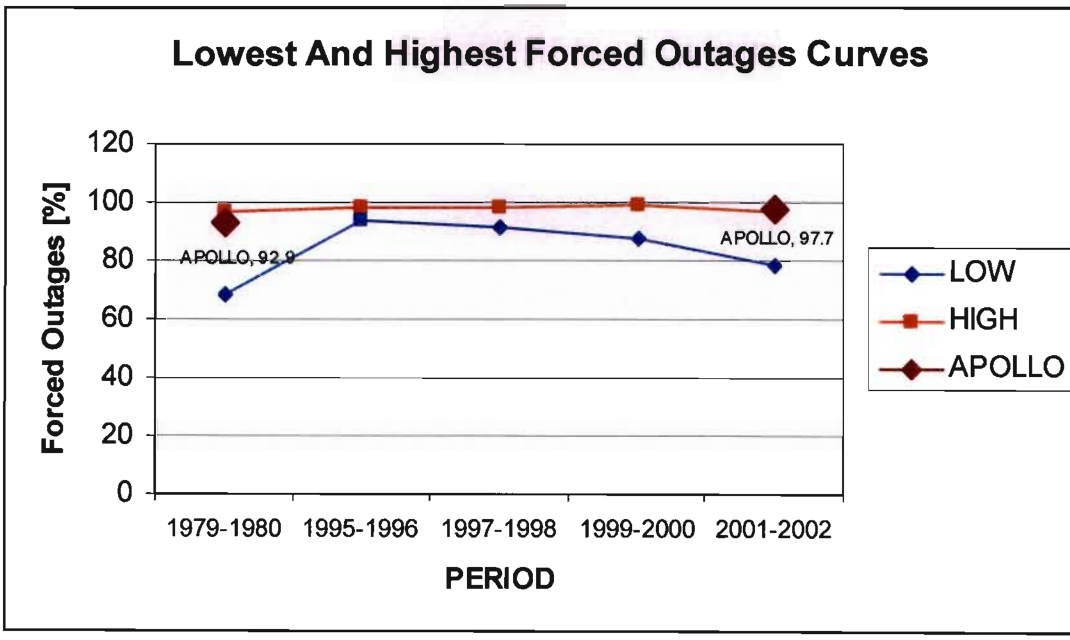


Figure 5.6 Lowest and Highest Forced Outages curves

6.5 CONCLUSION

There are nine schemes that met the similarity criteria. On average there were four schemes in each period that submitted performance data to Cigré. The Apollo compared favourable to the other schemes.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

- A database is the best way to store and analyse electrical performance information. The year 2002 performance data has been stored in the database. The data was populated into the database from the Apollo control room operator's Daily Log Records.
- This data was refined and coherently arrange to be in a format that gives the performance information according to the Cigré specifications.
- The database is generic and thus can be applied to all the Point to point HVDC schemes.
- The Apollo performance data compares favourable with other similar international schemes.
- The fault logging procedure is adequate in as far as accurate data capturing. The analysis ability depends entirely in the manner in which the data is stored. Data analysis improves when data is stored in the database rather than on daily log sheets.

6.2 Further Work

- Further work in capturing historical data dating back to the nineteen eighties will further enrich the knowledge of the scheme.
- Further work can also be carried out in the analysis and computation components of the database.
- Further work in the integration of the database with some of the automatic schemes in the control room.
- Work also need to be carried out in associating pole numbers to the distance of fault for purposes of fault location.

CHAPTER 6

CONCLUSIONS

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APPENDIX A

Features That Make The Database User Friendly

STEP 1

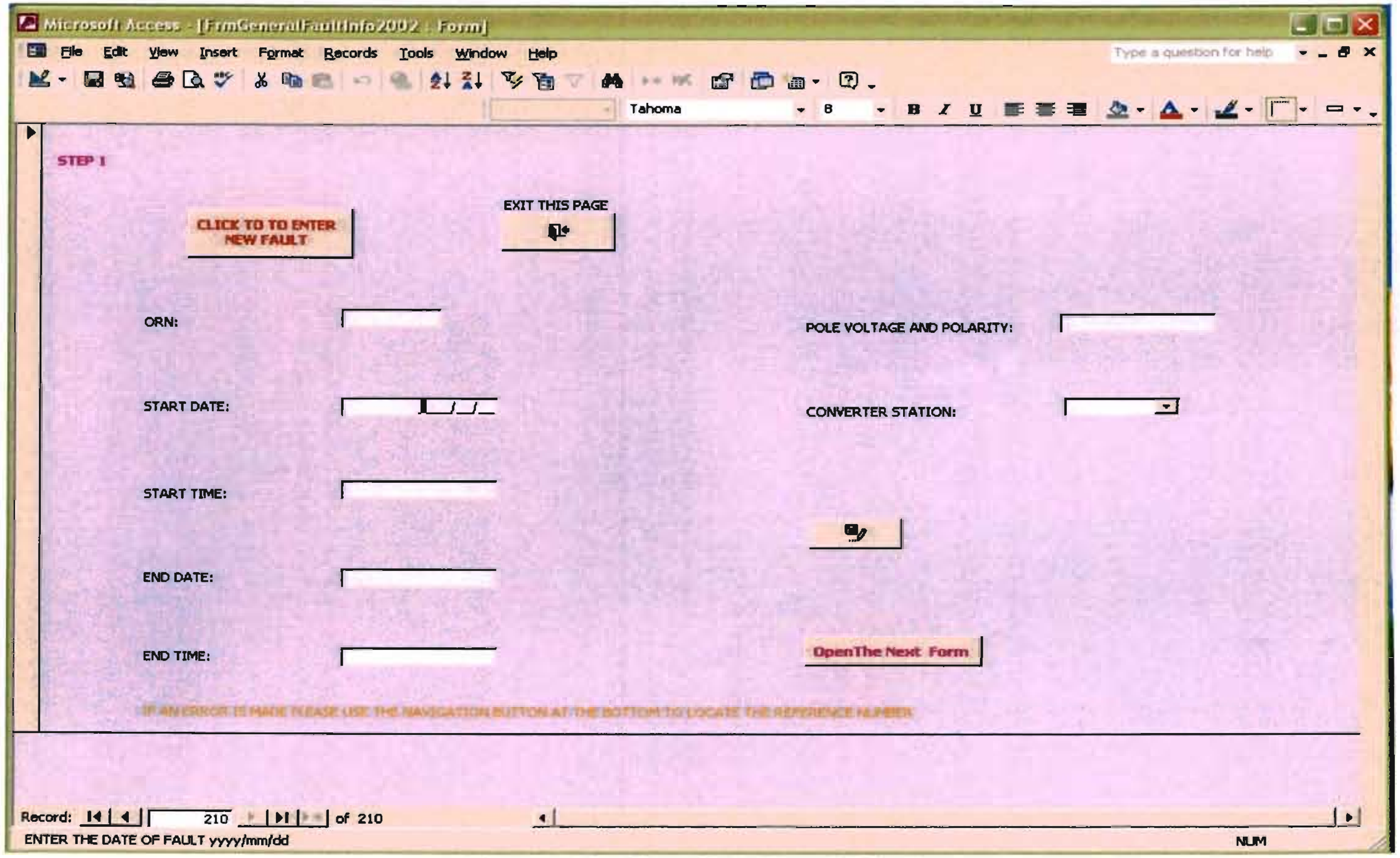

Figure A1. Start Date Input Mask

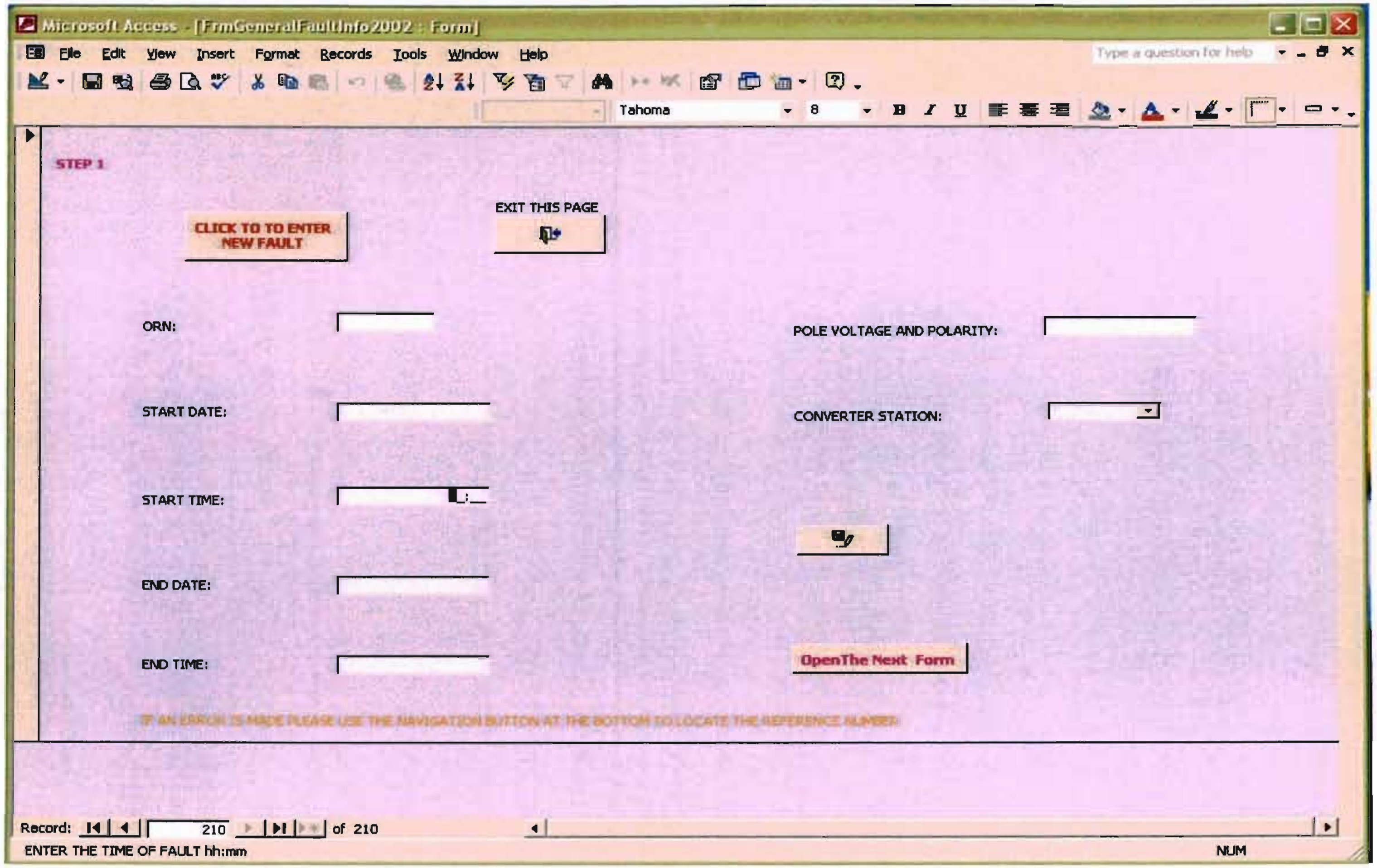

Figure A2. Start Time Input Mask

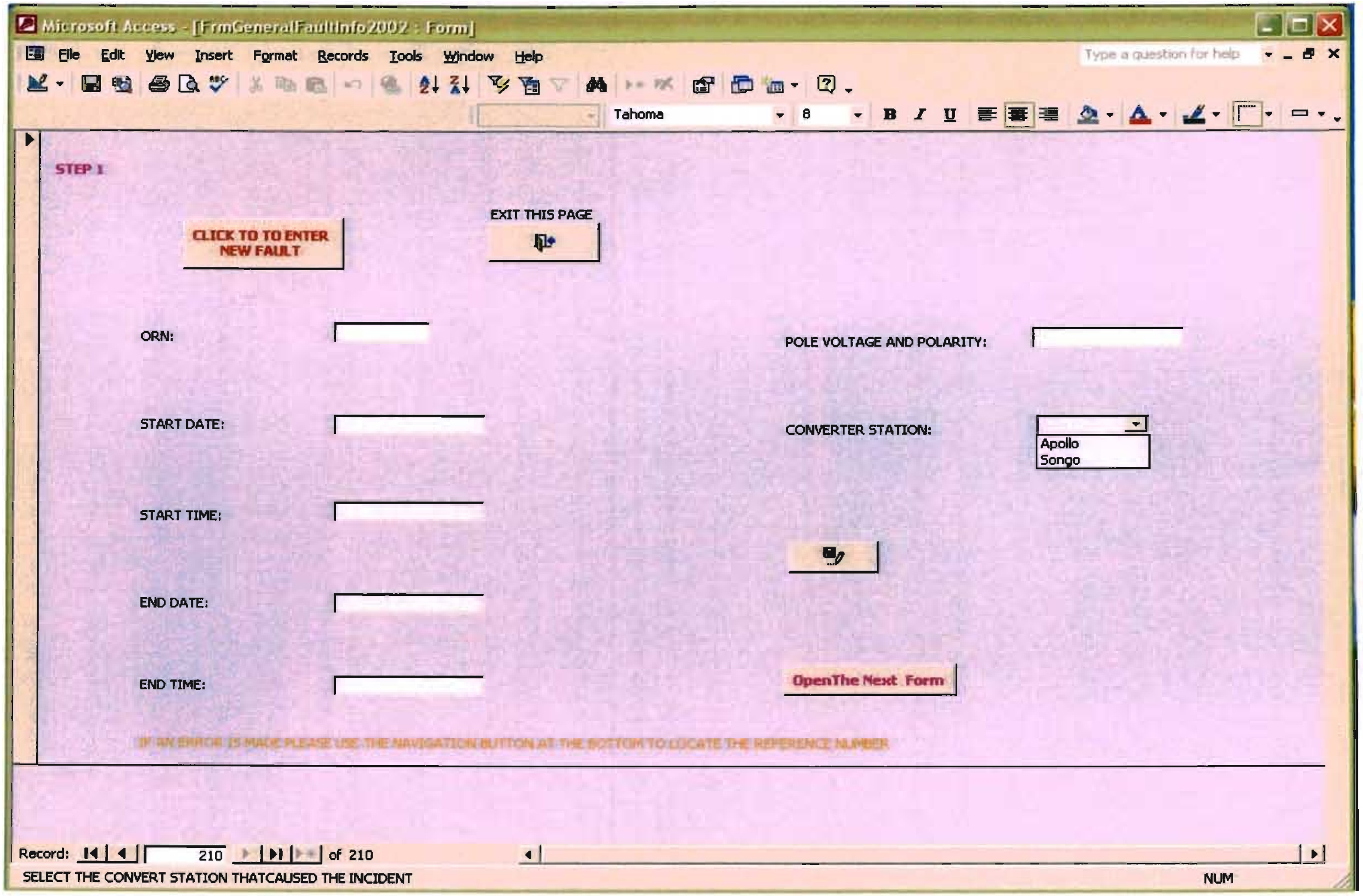

Figure A3. The drop Down Arrow

STEP 2

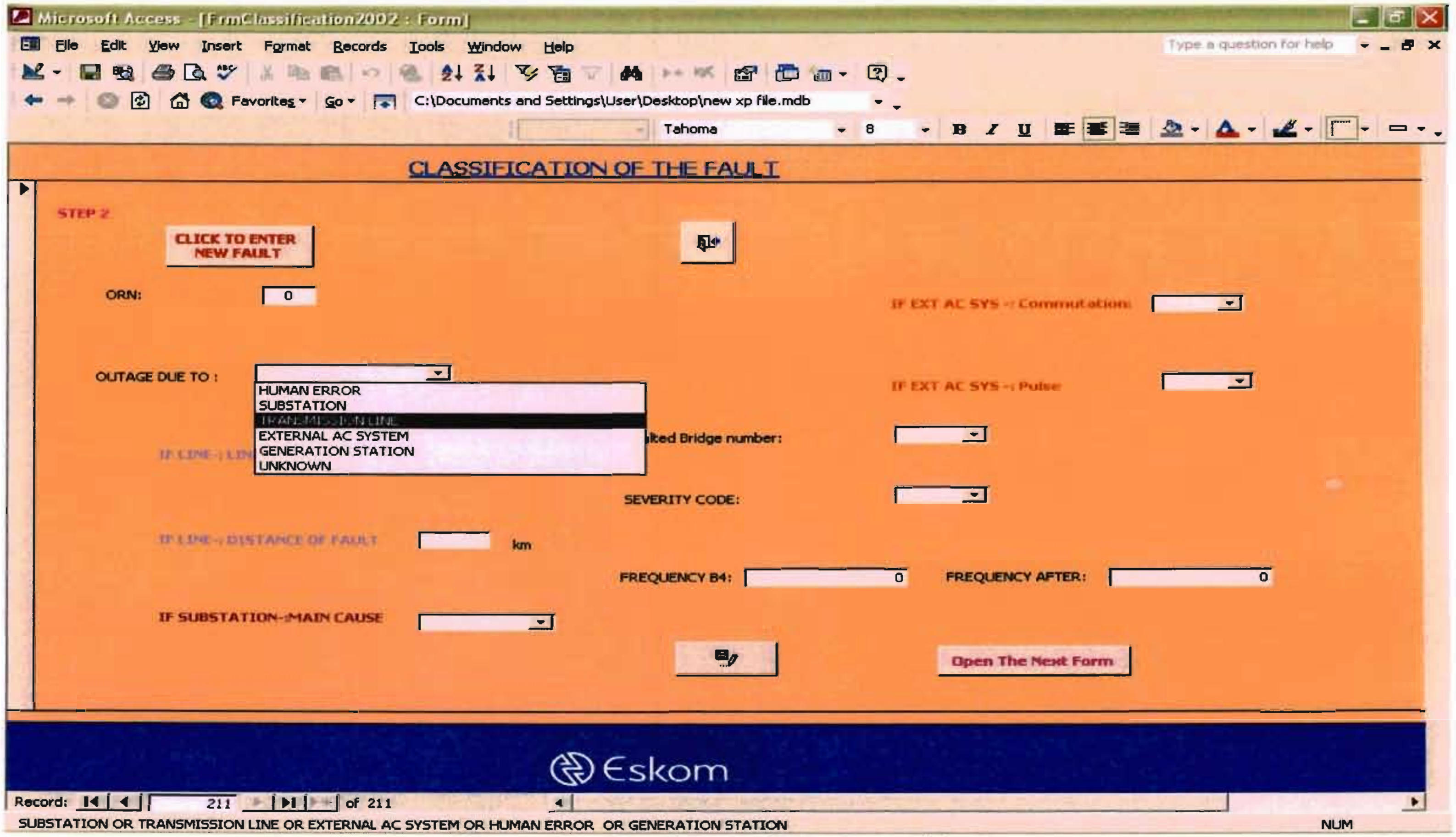

Figure A4. The Outage Drop Down Menu

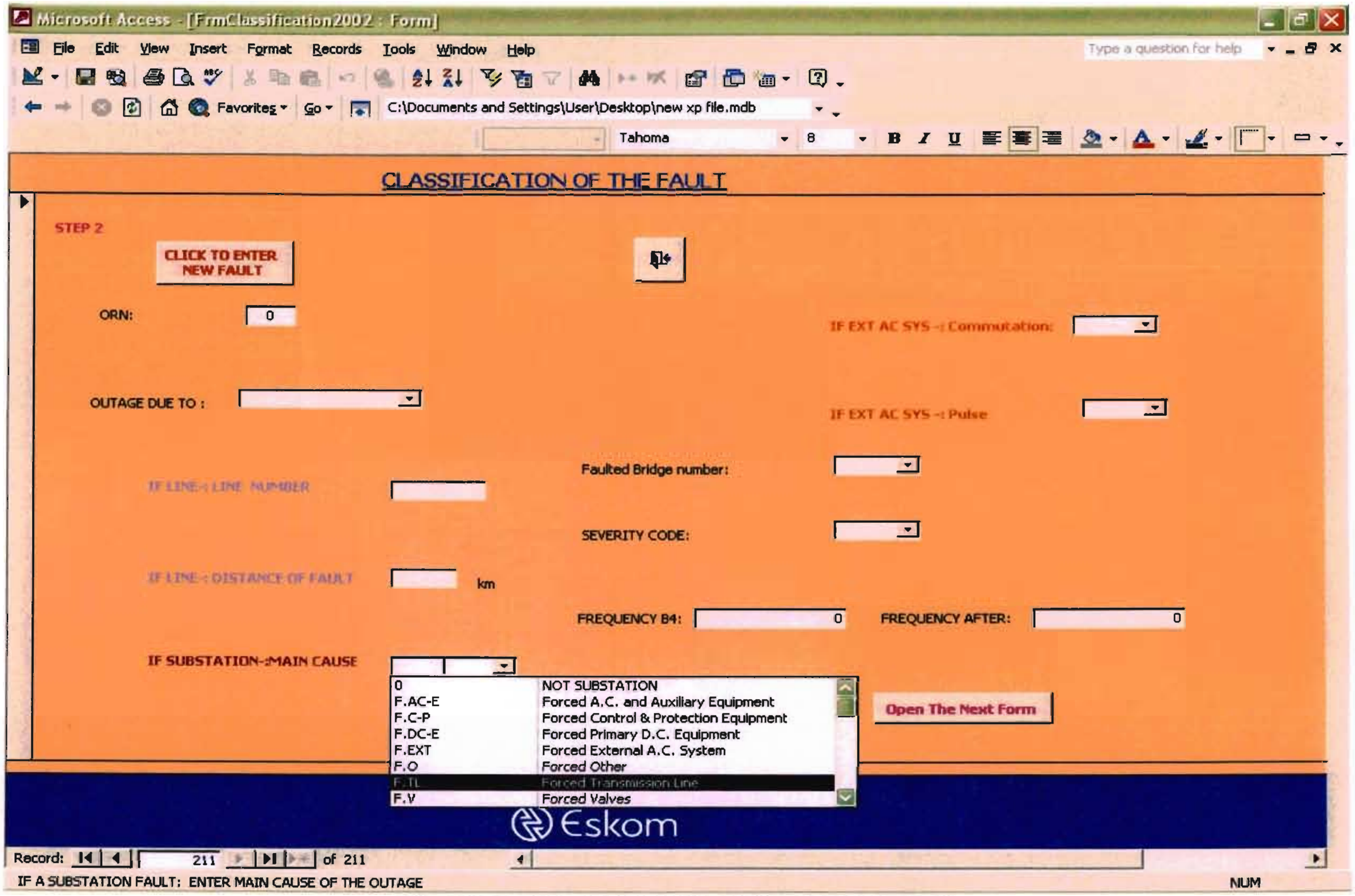

Figure A5. The Main Cause Drop Down Menu

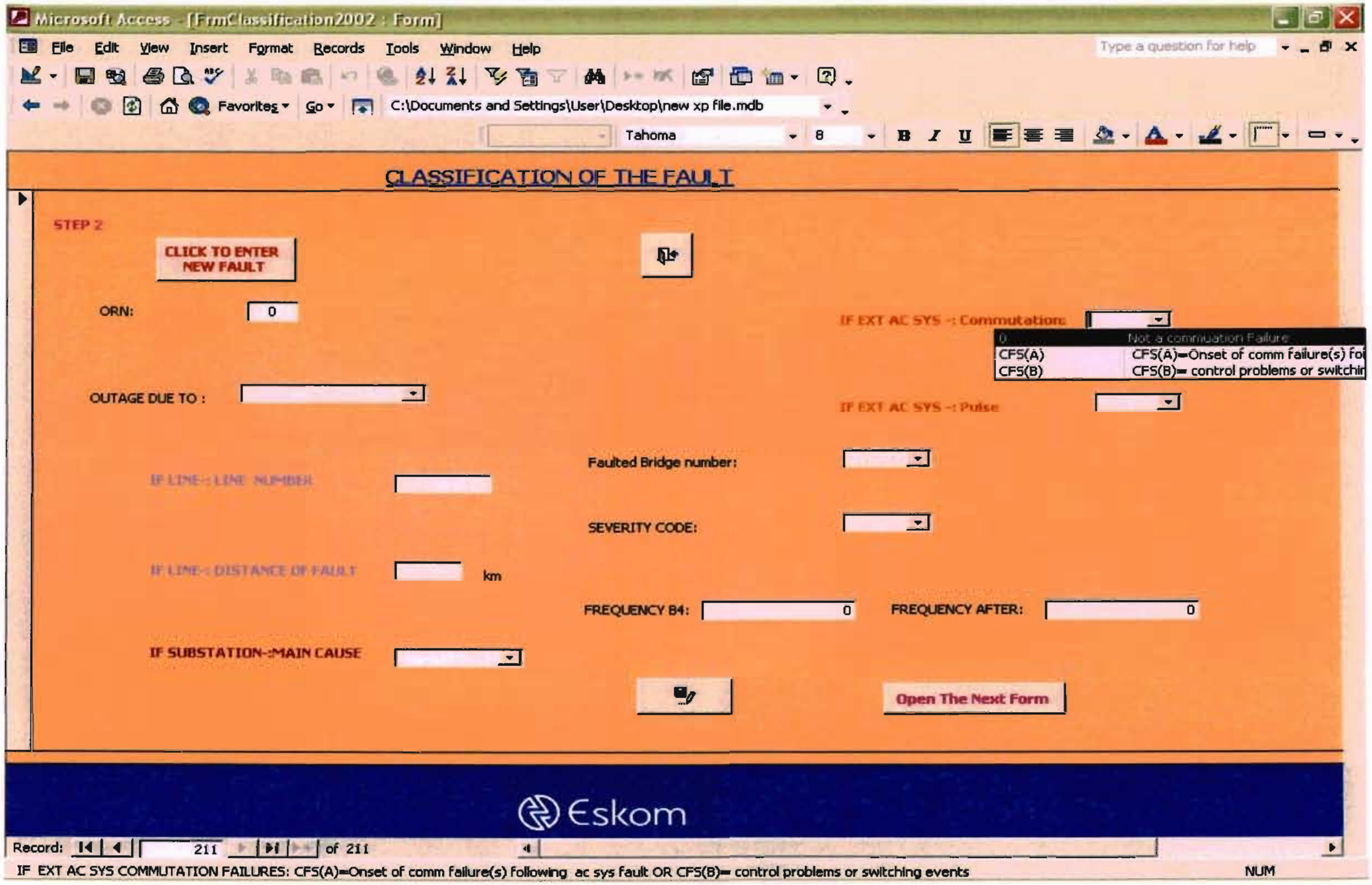

Figure A6. The Commutation Drop Down Menu

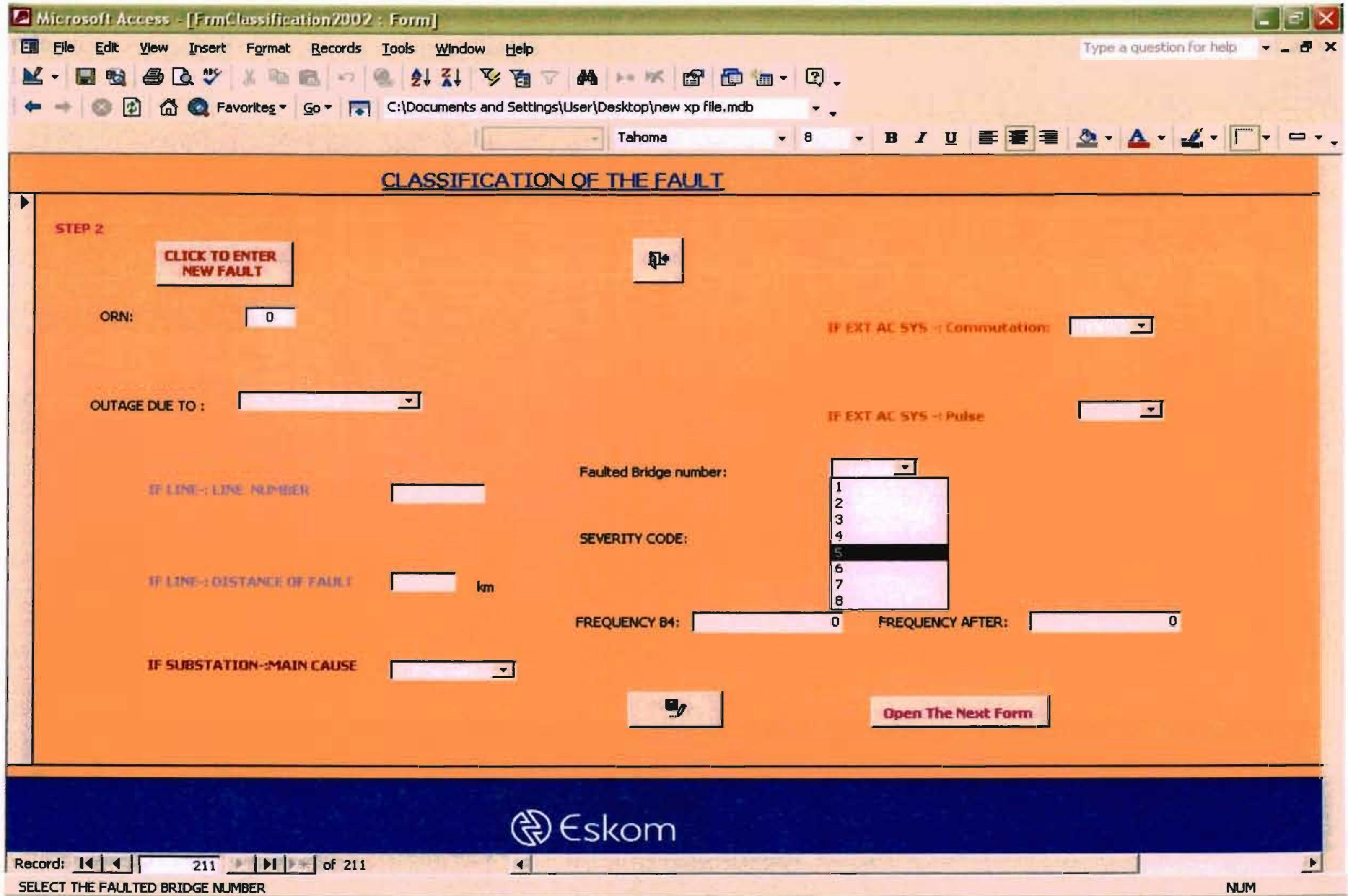

Figure A7. The Bridge Drop Down Menu

STEP 3

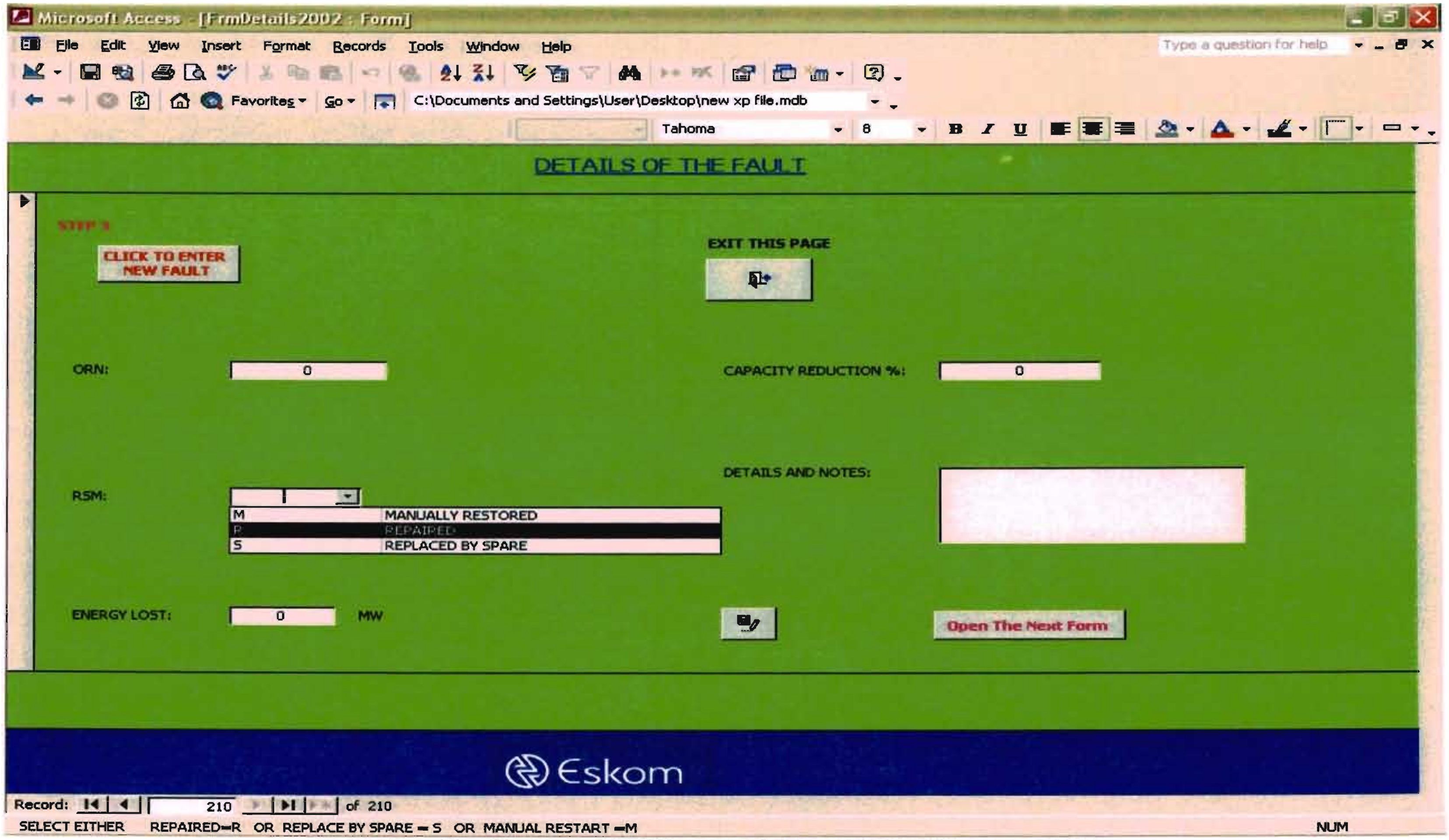

Figure A8. The Repair, Spare or Manual Restart Drop Down

STEP 4

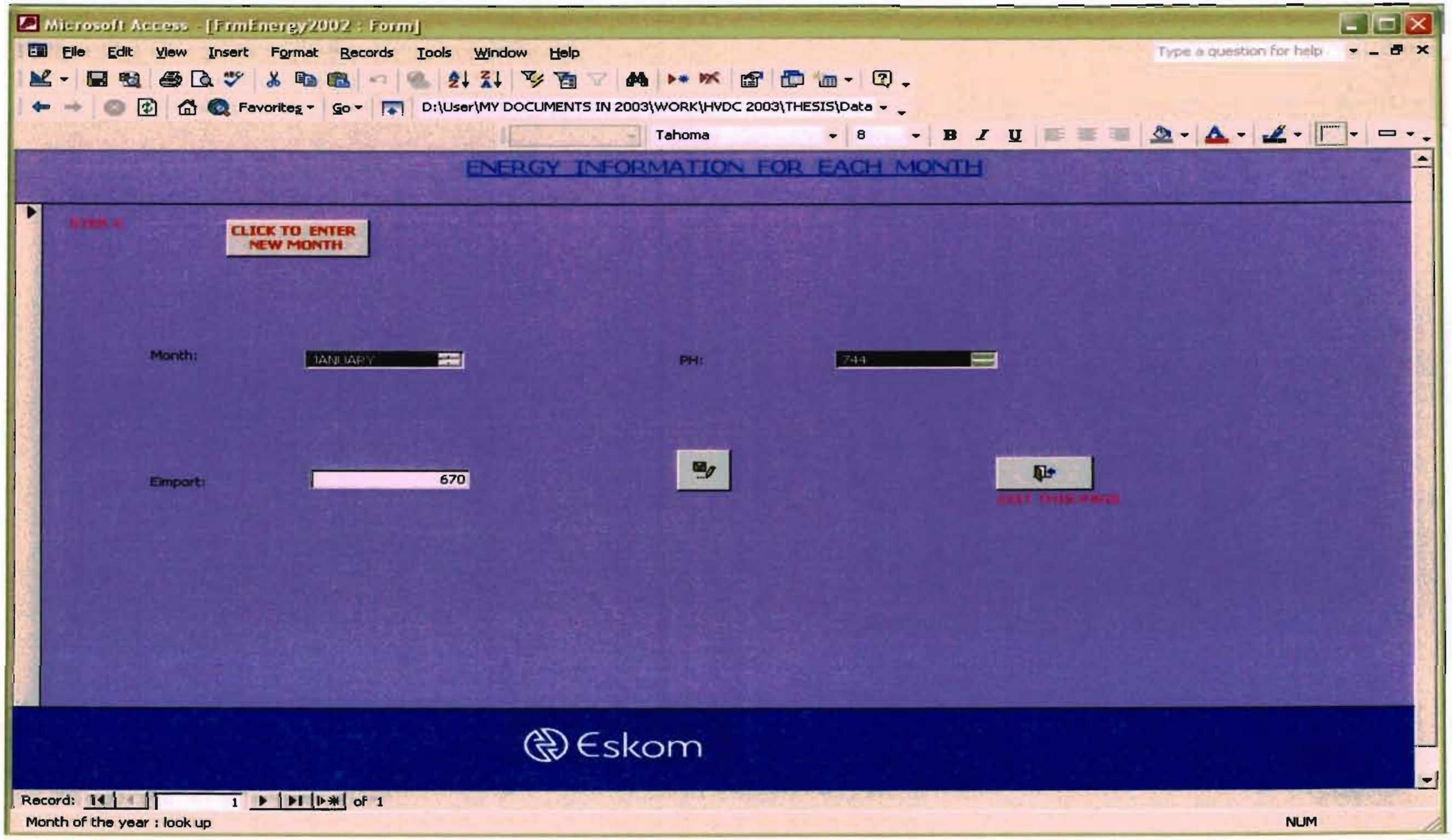

Figure A9. The Last Input Page

APPENDIX B

This Log Form is lifted from the Cigré Protocol [9]

OUTAGE LOG FORM

System: ____________________

Station: ____________________

Year: ____________________

	Outage Code *	
Outage due to faulty equipment	Forced:	Scheduled:
A.C. and Auxiliary Equipment	F.AC-E	S.AC-E
Valves	F.V	S.V
Control & Protection Equipment	F.C-P	S.C-P
Primary D.C. Equipment	F.DC-E	S.DC-E
Other	F.O	S.O
Transmission Line	F.TL	S.TL
External A.C. System	F.EXT	
Scheduled outage for planned maintenance:		S.PM

Outage Reference Number	Date & Time		Actual Outage Duration AOD	Outage Derating Factor ODF	Equivalent Outage Duration EOD	Outage Code	Severity Code BP,P,C	Description of Event, Equipment or Component Causing Outage	Repaired-R Spare-S Man Restart-M
	Start	Finish							

* See Section 4 or Appendix B for outage code subclassification for forced or for deferred scheduled outages.

APPENDIX C

All the HVDC systems that are used in Chapter 6 are listed and Technical Specifications are dealt with in details. All the data used in this Appendix was taken from the Companduim compiled by Cigre. [13]

THE CU HVDC SCHEME

Between: Coal Creek, North Dakota and Dickinson, Minnesota

Power Company:Cooperative Power (CP), Eden Prairie, MN United Power Association (UPA), Elk River, MN

Manufacturer: ASEA, Sweden

Commissioned: August, 1979

Main Purpose: Base load, bulk power transmission between Coal Creek lignite mine-mouth generation plant to Dickinson; reversal transmission is possible.

Main Data: Bipole 1000 MW at ± 400 kV and 1250 A/pole.

Overload capacity :

1375 A continuously

1500 A for 1 hour or continuously if the temperature is below 8°C

max. 1820 A during damping control sequence

AC Networks: At both terminals, two 3-phase converter transformers (Wye-Delta and Wye-Wye) per pole, 1 for each 6-pulse group at each terminal

Coal Creek: 4 @ 308/339 MVA. 235 kV + 20 %/174.5 kV

- 10 %/174.5 kV

(+16 and -8 taps @ 1.25 %/tap)

connection to the 230 kV AC system

Dickinson: 4 @ 292/321 MVA. 350 kV + 21.25 %/165 kV

- 8.75 %/165 kV

(+17 and -7 taps @ 1.25 %/tap)

connection to the 345 kV AC system

Minimum short circuit ratio of 3.5

HVDC System:

Overhead lines : 701 km (435.8 miles)

Line towers: self supporting lattice steel structures

Conductors: 2 x 1150 mm^2 ACSR/pole (d=1.504 in)

Shieldings: 2 x 130 mm^2 steel wire (d=0.5 in)

Insulator leakage: 25 mm/kV.

Electrodes: The Coal Creek Terminal is designed with 12 vertical electrodes, each approximately 60 meters deep and 0.3 meters in diameter ; coke backfill is used.

The Dickinson Terminal is designed with 15 vertical electrodes, each approximately 75 meters deep and 0.3 meters in diameter ; coke backfill is used.

Resistance/electrode: total less than 0.1 ohm

Electrode lines : 2 x 620 mm^2 ACSR (d=1.108 in.)

Coal Creek: length $\simeq$ 10 km (6.6 miles); R $\simeq$ 0.38 ohm

Dickinson: length $\simeq$ 20 km (12.5 miles); R $\simeq$ 0.72 ohm

On-line metallic return switching is available.

DC Filters: Dickinson : third-order high pass, tuned to the 12th harmonic

Coal Creek : High pass type, tuned to the 12th harmonic

HVDC Valves: The thyristor valves are housed indoors, and they are designed as "Quadruple" valves. Three quadruple valves form a 12-pulse converter unit.

Each quadruple valve has 4 valve sections in series connection. Each valve section has 30 modules, each with 6 thyristors in series connection, giving the total of 180 thyristors in series connection/valve arm and none in parallel. This makes 720 thyristors in one quadruple valve or 2160 thyristors in one 12-pulse converter unit for 400 kV DC and 1250 A. The valve structure is air insulated and air cooled.

The smoothing reactor is placed on the neutral side and is designed for 0.4 Henry.

Filters and Shunt Banks:

Both terminals are provided with harmonic filters:

Coal Creek: 2 filters each for 11th and 13th harmonic and 2 high pass filters

Quan.	Harm.	MVAr *	C=μF	L=mH	R=ohm
2	11th	32.3	1.55	37.3	1.6
2	13th	33.9	1.63	25.6	1.5
2	HP	56.5	2.72	4.3	78
		Shunt	Banks		
1	SH	102.8	4.94	--	--

* MVAR at 235 kV

Dickinson: 2 filters each for 11th and 13th harmonic and 2 high pass filters

Quan.	Harm.	MVAr *	C=μF	L=mH	R=ohm
2	11th	31.4	.678	85.5	4.8
2	13th	33.4	.72	57.7	4.4
2	HP	71.7	1.55	7.9	143
		Shunt	Banks		
3	SH	114.7	2.48	--	--

- MVAR at 350 kV

RIHAND - DELHI HVDC PROJECT

Between : Eastern and Western regions of Uttar Pradesh, India.

Geography :

a. Rihand terminal at Rihand, Uttar Pradesh, India

b. Delhi terminal at Dadri, Uttar Pradesh, India (about 50 km from Delhi).

Power Co. : National Thermal Power Corporation Ltd. NTPC Bhawan,

Scope Complex - 7, Institutional Area, Lodhi Road, New Delhi - 110 003, INDIA

Manufacturer : M/s. Bharat Heavy Electrical Ltd., India, and M/s Asea Brown Boveri, Sweden

Commissioned : For commercial operation: April 1992

Main Purpose : To transfer bulk power from NTPC's Rihand-Singrauli Thermal Power generating complex to the load centre in the National Capital Region around Delhi.

Main data : For the HVDC Plants :

Nominal Power Rating : 1500 MW at Dadri A.C. side

1568 MW at Rihand end. (Bipolar)

Two-hour over-load : 1650 MW (Bipolar) at Dadri AC side

This also becomes the continuous rating for ambient temperatures equal to or lower than 33 deg. C. (normal rating corresponds to 50 deg. C. ambient).

5 sec. overload rating : 2000 MW (Bipolar)

Nominal voltage : 500 kV DC (Monopolar)

Reduced voltage : 400 kV DC (Monopolar)

Refer to fig. 1.0 for main circuit arrangement.

A.C. Networks :

AC system voltages : 400 kV at both Rihabnd and Dadri.

Converter transformer type : 3 Nos. Single phase winding transformers per pole/station

MVA rating : Rihand : 315 MVA, Dadri : 305 MVA

Voltage rating : Rihand : 400/213 kV, Dadri : 400/206 kV

Tap changer ranges : + 14/-10 in steps of 1.25 %

Short circuit Ratio :

(1) ESCR = 5.0 at Rihand, 3.5 at Dadri (Normal SCR level)

(2) ESCR = 2.5 at Rihand and Dadri (Minimupm SCR level)

A.C. Filters :

Three types DT (double tuned), DTHP (double tuned high pass) and hign pass are installed. (Refer to fig. 3.1)

Harm.	MVAr	C = F	L = mH	R =	Type
3/36	40.1	CH=0.77 C1=1.99	LH=14.13 LL=416.6	RH= 480 RL=13700	DT
11/13	39.0	CH=0.77 CL=31.69	LH=94.43 LL= 2.29	R = 6420	DT
5/27	70.5	CH=1.39 CL=6.11	LH=12.38 LL=54.78	RH= 370 RL= 2500	DT
HP24	38.8	C= 0.77	L= 23.83	R= 723	DTHP

Legend :

XH --> High voltage component

XL --> Low voltage component

HVDC System :

a). Line data :

Length : 814 kms.

Pole Conductors : Quad Bersimis- ACSR

457 mm spacing.

Sag 17 m at 75 deg.C

Ground wires : 11.1 mm dia (7/16")

Sag 11.13 m

Spacing between pole conductors: 12.4 m

Height of pole conductor, at tower, above ground: 28.0 m

Spacing between ground wire: 9.5 m

Height of ground wire, at tower, above ground: 36.2 m

Shielding angle : 10 deg.

<u>b). Electrode line data</u> :

Conductor: ACSR - 2 conductors (Bersimis) one on each side of tower.

Spacing between conductors: 1.5 m

Height of conductor at tower above ground: 1.5 m

Max. sag: 7 m

Cables: Nil

<u>Electrode</u> :

Rihand-Delhi HVDC system utilizes land electrods for ground return. It consits of double concentric rings. Further each ring is divided into a number of segments. In the event of one segment failing the load will automatically get distributed in the other healthy segments. In case one full ring is kept under shut down the maximum continous reserve capacity available will be about 60% of the rated load.

Electrode details

TERMINAL STATION	DADRI	RIHAND
ELECTRODE STATION	DANKAUR	CHAPKI
Radial distance	25 km approx	25 km approx
Type of Electrode	LAND	LAND
Electrode design	Double Ring	Double Ring
Electrode Backfill	Coke Breeze	Coke Breeze
Electrode Resistance	0.034	1.0

DC Filters

Single tuned and double tuned identical filters are installed at Rihand-Delhi.

Harmonic tuning	N° of Filters	C = F	L = mH	R =
12th Single Tuned	2	1.2	58.6	
12/24th Double Tuned	2	CH= 1.2 CL= 1.8	LH=42 LL=15.38	RL= 522

HVDC valves :

STATION: DADRI/RIHAND

Valve design: Quadruple, suspended, water cooled, air insulated

Valve arrangement in series: 12 pulse

N° of modules/valve in series: 16

N° of thyristors/ module: 6

Supplier : ABB/BHEL

Cooling system :

The thyristors are water cooled. The primary cooling circuit is a closed loop system which carries very low conductivity demineralized water and takes away heat from aluminium heat sinks. The heat is further dissipated to the atmosphere through evaporative coolers provided in the secondary water cooling circuit. The heat exchangers act as an interface between the primary and secondary water cooling systems.

Smoothing reactor :

The smoothing reactor consists of two parts, one oil filled reactor of 0.36 H close to the valve (with one bushing protruding into the valve hall) and the second an air-core smoothing reactor of 0.18 H in the D.C. yard.

The D.C. filter is tapped off between the series connection of the two smoothing reactors.

1 . Redundancy

AC-E.F At each station three identical banks (total nine sub-banks) have been provided. In case of failure of one bank, system can be operated upto rated power without any restrictions.

AC-E.SW As one and half breaker scheme has been employed, failure of any one equipment will not restrict power transfer capability.

AC-E.CP Main and backup protections operating on different principles are provided however where back up is not possible by a different principle, redundant protection is provided. Main and back up protections are duplicated with one system active and the other in stand-by mode.

AC-E.AX The A.C. auxiliary system has a number of redundant components including the incoming and supply feeders (11 kV at Rihand, 6.6 kV at Delhi). Failure of any one component will not affect power transfer capability.

V.E Out of the 96 thyristor levels of a valve, 3 thyristors levels are redundant.

C-P.L The HVDC controls and protection are fully redundant with each system having main and backup protections within it.

C-P.M Controls are duplicated with facility to control from a mimic as well as VDU display and keyboard. The processors are duplicated.

C-P.T Telecommunication channels over power line carrier are duplicated at the pole level. Media of communication is only power line carrier.

2 . Reserve system

AC.E.AX As a reserved to A.C. auxiliary power (6.6 kV) feeders, diesel generator set (2 * 450 kW) has been provided, at Dadri terminal to meet emergency and essential requirements.

C-P.L Standby system is in hot standby mode always and takes over automatically in case of failure of main system.

C-P.M Failure in mimic or VDU system enables control from the other.

3 . Spare part

As a major equipment, one unit each of converter transformer (1 phase, 3 winding) and smoothing reactor have been purchased for each station. For other systems, components in lots have been bought. For example for AC filters, reactors, resistors and a few capacitor cans have been bought. Regarding the time it is difficult to give a definite figure at this stage since it depends on the type of fault, work associated with respective replacement etc.. Since we have just commissioned the system, enough operating experience to judge these factors to reasonable accuracy is lacking

THE ITAIPU HVDC SCHEME

Between:Foz do Iguaçu at the border of Brazil and Paraguay to Sao Paulo Brazil

Power Co.: Furnas Centrais Elétricas S.A. Brazil

Manufacturer:ASEA Promon HVDC consortium, formed by ASEA Sweden, ASEA Elétricas Ltda, Brazil and Promon Engenharia S.A. Brazil

Commissioned:

Bipole 1 **1**. stage: ± 300 kV, 1575 MW in July 1984

2. stage: + 300kV,2362.5 MW in April 1985 - 600kV

3. stage: ± 600 kV, 3150 MW in May 1986

4.stage: ± 300 kV, 1575 MW { commissioned Bipole 2.

5.stage: + 300 kV, 2362,5 MW { at the - 600 kV { same time by

6.stage: ± 600 kV, 3150 MW { August, 1987

Main purpose: Bulk power supply from the great Hydro Power station (12600 MW) at Foz do Iguaço to the São Paulo industrial area. The power is generated by 18 hydro generators, nine of them are designed for 60 Hz with a capacity of 765 MVA, P.F. = 0,95 and the other nine are designed for 50 Hz with a capacity of 823 MVA, P.F. = 0,85 supplying the HVDC system.

Main data: The HVDC system consists of two bipolar transmission systems, each one designed for 3150 MW at ± 600 kV D.C. and 2625 A.

overload capacity: 5 seg. --------- 3260 Amp.

20 seg. ------- 3000 Amp.

A.C. networks:

24 single three phase winding converter transformers are used at each terminal which means three transformers/12 pulse unit, forming four converters per bipole.

Foz do Iguaçu: 50 Hz, 314 MVA

500/_ 3 kV+20 x 1,25 % kV - 6 min. short circuit capacity: 16373 MVA

Sao Rogue: 60 Hz, 300 MVA

345/√ 3 kV+20 x 1,25 % kV - 6 min. short circuit capacity: 7800 MVA

(light road)

Synchronous

Compensator: Sao Roque - 4 x 330 MVAr

AC filters: Harmonic filters are provided at the 50 Hz and 60 Hz side. Shunt capacitor bank only at the 60 Hz side

50 Hz Side - FOZ DO IGUACU

AC FILTERS

TYPE	HARMONIC	MVAr	UNITS	TOTAL
1	3º/5º.11º/13º. HP1A,HP1B	349.0	2	698.0
2	11º/13º. HP2	280.3	3	840.0

TYPE 1					**TYPE 2**	
COMPON.	3º/5º	11º/13º	HP1A	HP1B	11º/13º	HP2
C1(µF)	0.814	1.691	0.916	0.929	1.691	1.858
L1(mH)	830.0	41.95	19.86	7.715	41.95	9.41
C2(µF)	2.986	49.15	-	-	49.15	-
L2(mH)	226.6	1.44	-	-	1.44	-
R(ohms)	2930.0	0.444	1060.0	305.0	0.444	170.0
MVAr	70	134.3	72	72.7	134.3	146.0

60 Hz Side - SAO ROQUE

AC FILTERS

HARMONIC	MVAr	UNITS	TOTAL
11°. 13°	220.8	3	662.4
11°. 13°. 3°/5°	279.8	1	279.8
3°/5°. HP2	296.0	1	296.0
HP1	237.0	4	948.0
HP2	296.3	1	296.3

COMPON.	3°/5°	11°	13°	HP1	HP2
C1(μF)	1.160	2.417	2.468	5.273	6.591
L1(mH)	405.0	24.06	16.87	2.318	2.318
R(ohms)	2500	3990	3300	46.76	46.76
C2(μF)	4.281	-	-	-	-
L2(mH)	110.1	-	-	-	-
MVAr	59.0	109.4	111.4	237.0	296.3

Shunt capacitor bank: 2 x 294,0 MVAr, 6,45 μF

HVDC System: Route length:

Bipole 1 (South Line): 807 km

Bipole 2 (North Line): 818 km

Overhead lines:

Conductors: 4 x 689 mm^2 ACSR (1272 MCM)

Shielding:7 strand, galvanized steel wire 9.5mm)

Line towers: 23 % are selfsupported and 77 % are guyed lattice steel structures

The two bipolar line systems are separated 10 km from each other as a minimum.

Electrodes: The electrode switching houses are situated far from the stations:

Foz do Iguaçu: Bipole 1: 15,5 km

Bipole 2: 16 km

San Roque: Bipole 1: 67,2 km

Bipole 2: 66 km

conductors type: 2 x 689 mm^2, 1272 MCM

D.C. Filters:

STATION	BRANCH	BANK CAPACITANCE (µF)	TUNING FREQUENCY (HZ)	CH (µF)	L1 (mH)	R1 (ohms)	C1 (µF)	LH (mH)
Foz do	2°/6°	0.533	100/300			23.0	0.533	
				0.500	2111.0			1267.0
Iguacu	12°	0.715	600		-	1.32	0.715	
				1.285				35.04
	HP	1.570	1200		-	660.0	-	
				1.010				17.42
	2°/6°	0.558	120/360			18.0		841.0
				0.523	1401.0		0.5579	
S. Roque	12°	0.878	720		-	1.29		
				0.828			0.8753	28.42
	HP	1.570	1440		-	210.0	-	7.78
				1.570				

HVDC Valves: The Itaipu HVDC System uses thyristor valves, indoor type, water cooled and isolated by air. Mechanically, the valves are built up as quadruple-valves forming a converter. One single valve is made up of 8 thyristor modules series connected, containing 12 thyristors with voltage dividers and control circuits.

THE PACIFIC INTERTIE SCHEME

Between: Celilo, The Dalles, Oregon and Sylmar, California

Operated by: Celilo : Bonneville Power Administration, Portland

Sylmar : Los Angeles Department of Water & Power

Manufacturer:

ASEA, Sweden, and General Electric

Commissioned:May 1970, upgrade 1985 (by adding a thyristor bridge in serie).

Expansion 1989 (by adding parallel converters).

Main Purpose:

The generation resources of the Northwest are made available to the Southwest during peak load periods. In return, the Northwest is provided with energy during off peak period (Capacity-Energy Exchange).

The transmission of surplus hydro power from Northwest when available.

MAIN DATA :

Bipole : 2000 MW at ± 500 kV and 3100 A/pole.

Monopolar : 1550 MW with earth return or 1000 MW with metallic return.

AC NETWORKS :

At both terminals, three single phase converter transformers are used for each of the four 6-pulse converter groups/pole, and three single phase-3 winding converter transformers are used for the expansion converters (1 & 2).

Celilo Converters 3 & 4 :

6 banks-289 MVA, 3 phase, $235^{+13\%}_{-2\%}$ /113.3 kV_{LL}

+ 15%

2 banks-268 MVA, 3 phase, 235 /85.kV_{LL}

- 2%

<u>Celilo Converters 1 & 2</u> :

+ 22.5%

2 banks-639 MVA, 3 phase,525 /205.3 kV_{LL}

- 5%

The pre-expansion project transformers are connected to the 230 kV A. C. system. The expansion transformers are connected to the 500 kV A.C. system. Celilo short circuit capacity : Minimum 17.000 MVA. Normal ESCR without filters is 6.7. Minimum ESCR without filters is 5.5.

The transformers are connected to the 230 kV

A.C. System.

Short circuit capacity : min. 6750 MVA

<u>Sylmar Converters 3 & 4</u> :

+ 15%

6 banks-289 MVA, 3 phase 235 /113 kV_{LL}

- 4%

+ 15%

2 banks-268 MVA, 3 phase, 235 /85.5 kV_{LL}

- 4%

The transformers are connected to the 230 kV

A.C. system. Short circuit capacity :

min 10.000 MVA

CELILO AC FILTERS (single Tuned)				
Harm.	MVAr	C = F	L = mH	R =
5	51.3	2.469	114	0.86
7	25.7	1.260	114	1.18
11	26.6	1.322	44	0.72
13	19.0	0.946	44	0.86
HP 18	77.8	3.9	5.5	40
HP 27	116.7	5.85	1.67	56.7

CELILO AC FILTERS (double Tuned)					
Harm.	MVAr	C_{HV} =F	C_{LV} =F	L_{HV} =mH	L_{LV}=mH
13/24	140	1.34	3.34	16.98	6.81
36/48	115	1.11	13.27	3.68	0.31

HVDC-system :

Route length = 1361 km

Overhead lines :

Conductors : 2 X 1171 mm^2 ACSR/pole.

Note : Conductor cross-sectional area does not include steel reinforced core.

Line towers : Self-supporting and guyed towers are used. All self-supporting towers are steel structures. Guyed towers for the Southern section are steel and for the northern section aluminium.

Shieldings : The northern section has a single steel shielding wire of 127 mm^2. The southern section has 2-steel shielding wires each of 97 mm^2.

Insulator leakage : varies from 1.8 to 2.6 cm/kV (for 500 kV)

Electrodes :

At Celilo : the ground electrode is located 10.6 km from the converter station, in Rice Flates. The electrode is designed as a ring type 3255 m circumference, 1067 cast iron anodes, and 2' X 2' coke backfill is used. Total resistance in 2 parallel electrodelines and ground electrode = 0.43 ohms.

At Sylmar : the sea electrode is located 48 km from the converter station, in the Pacific Ocean and consists of a linear array of 24 horizontal electrode elements made up of silicon-iron alloy rods suspended 0.5 to 1 m above the ocean bottom and located within concrete enclosures. Total resistance in 2 parallel electrode lines and sea electrode = 1.13 ohms.

Electrode lines :

At Celilo : 2 X 644 mm^2 ACSR conductors in parallel supported by the D.C. line towers.

At Sylmar : 2 X 644 mm^2 ACSR conductors in parallel are used for the first 35 km, supported by the 230 kV line towers. For the remaining 13 km, two parallel paper-insulated underground cables are used, each with a 633 mm^2 Cu-conductor.

DC Filters :

Each pole has one double-tuned HP and 6th harmonic filter and one single-tuned filter tuned to the 12 th harmonic. The expansion project added one 12/24 harmonic filter and one 2/12 harmonic filter. The filters are connected between the pole and the electrode lines.

CELILO AND SYLMAR D.C. FILTERS				
Harm.	C_{HV}= F	C_{LV}= F	L_{HV}= mH	L_{LV}= mH
12	0.39		125.3	
6/HP	3.52	15.01		10.55
2/12	1.1	0.34	225.87	741.2
12/24	0.4	0.8	61.08	30.54

HVDC-Valves :

Mercury arc valves are used for 6 of the converter groups. In 1984 two additional solid state thyristor groups were added at the highest kV-BIL level. The valves have air-cooled anodes and a water-cooled cathode.

There are 6 anodes/valves. The thyristor groups are water cooled valves. Six valves and one bypass-valve form a 6-pulse mercury-arc converter group for 133 kV ; the thyristor groups operate at 100 kV .

Each pole has 4 series connected 6-pulse converter groups. The smoothing reactors rated at 2000 A are placed on the high voltage side, designed at 0.4 H to 0.6 H at 400 kV D.C. and 10 mH at 500 kV D.C.

In 1989 expansion project converters were added in parallel with the mercury arc converters in each pole. The expansion converters are 12 pulse converters capable of operation at 367, 400 and 500 kV in order to match the voltage levels of 3 or 4 group mercury arc converter operation in parallel. The expansion converter valves are water cooled. The valves are arranged in a quadruple valve arrangement. Each valve branch includes 4 series connected modular units, and each modular unit consists of 30 thyristor levels. The expansion smoothing reactors are placed on the high voltage side and are rated at 0.5 H, 1100 A.