SYNCHRONOUS TRANSMISSION CIRCUIT BREAKER DEVELOPMENT

Final Report

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ABSTRACT

The need for the development of a synchronous transmission breaker is discussed and the basic preliminary specifications for such a circuit breaker are established and tabulated.

The initial exploratory work designed to establish the preferred designs for a synchronous pulse generator, (or current zero predictor), for an operating mechanism and for a suitable interrupter are described in detail.

The experimental results obtained with vacuum interrupters and with axial blast interrupters, using pure SF_6 , mixtures of SF_6 and N_2 , and high pressure liquid SF_6 are reported.

The results are then evaluated and the performances obtained with each interrupting media are compared arriving at the end to a choice of a preferred design. This preferred design, an interrupter that uses SF_6 in the liquid state at pressures of 13.8 megapascals (2000 psi) is completely described. The results obtained in a series of experiments designed to establish limits of performance for this interrupter are also discussed.

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The principal investigators in this project were:
Mr. Ruben D. Garzon; Dr. Jiing-Liang Wu and Mr. Joseph V. Amato.

The participation of all others who contributed to the design, manufacture and testing of the models is gratefully acknowledged.

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PART I

EXECUTIVE SUMMARY

1.1 INTRODUCTION

During the last few years a rapid growth in the demand for electric energy has taken place. This growth has resulted in an even more rapid growth of fault currents.

Circuit breaker ratings have increased considerably; breakers rated 63kA are already in use, and ratings of 70 and 80kA are presently being introduced.

It is expected that further demands for increasing the interrupting capabilities of circuit breakers will continue, and if circuit breakers are to keep pace with the natural growth of the power systems these demands will have to be met. Research and Development will be needed to investigate new concepts that can result in an advance of the present state of the art.

In addition to higher interrupting ratings, there is a need for shorter interrupting times. This need is readily appreciated when the stability of the power system and the thermal and mechanical burdens imposed upon the equipment are considered.

Two cycle circuit breakers are presently available, but the need for one cycle breakers is being expressed by many system engineers.

Another factor that will influence the design of future power circuit breakers is the overall size of the breaker, specially when it is being used as part of a gas insulated station.

In the past the basic approach to higher interrupting ratings had been to increase the size of the interrupter. Obviously the parts in the larger interrupter become more massive and additional force is required if the operating times are to be maintained. Thus, larger interrupters result in larger and more expensive circuit breakers.

One logical approach to the solution of the problem, created by the increased fault current levels, appears to be the synchronization of the contact's opening to the occurrence of the natural zero of the alternating current. This concept of synchronous interruption has been a common application in the fields of electronics and mechanical rectifiers.

The total arc energy released into the interruption chamber can be greatly reduced by means of the synchronous operation, and depending on the arcing time and the degree of asymmetry, in the case of a nonsynchronous breaker, it is possible to achieve a reduction of arc energy of as much as 99%.

The reduction of the arc energy results in an overall reduction in the interrupter size and consequently of the whole circuit breaker.

Two basic requirements for synchronous interruption are:

A controlled contact parting time, and an operating mechanism capable of very high speeds.

The combination of these two requirements makes it possible for the circuit breaker to have a minimum interrupting time of 0.1 cycles, and a maximum of 0.8 cycles, depending on the asymmetry of the fault current.

Synchronous circuit breakers, as it has been briefly pointed out, can provide higher interrupting capabilities, and faster operating times with a very significant reduction in size.

To determine the feasibility of the synchronous breaker concept the present program was undertaken.

Several series of test were performed on different models and the results obtained are discussed and evaluated in this report.

1.2 SCOPE OF THE PROGRAM

A synchronous interrupter probably can be designed in several different ways. The variations will be primarily in the geometry since the basic operation concept is fairly well established.

Another variation in the concept could be the medium to be used in the interruption process. Presently the most common mediums used by the industry are: oil, compressed air, Sulfur Hexafluoride (SF_6), and vacuum.

Based on results of previous investigations it has been established that the two mediums most likely to succeed are SF_6 and vacuum. Both oil and air have been judged, in the past, to be inadequate for synchronous interruption.

This program was divided into two phases: Phase I was directed towards the establishing of bench marks, or preliminary data, required for establishing the characteristics in performance, that will lead to a final choice, between SF_6 or vacuum as the preferred interrupting media.

In this first phase, in addition to the investigations relating to the interrupting capabilities of the two mediums; alternate methods of current zero detection and several designs of operating mechanisms were evaluated.

The second phase of the project constituted of a final series of tests performed on the model interrupter chosen from the two interrupting mediums tested, (vacuum and SF_6), during the first phase of the program. The tests were directed towards obtaining data that can be used to demonstrate the capability of the chosen interrupter for meeting the rating that had been established as a goal.

1.3 GENERAL SPECIFICATIONS PRELIMINARY OBJECTIVES

Previously, it had been mentioned that higher interrupting currents, and shorter operating times were among the objectives of this program. It was also indicated that a reduction in the size of the circuit breaker was highly desirable.

For the purpose of this program system voltage limits of 362kV and 145kV were chosen as the maximum and minimum operating voltages. It was further decided that, ideally, the interrupters will be common for the different voltages, and that they will be utilized on a modular basis. For the 145kV voltage class a single interrupter would be required, while two interrupters in series will be needed for the 362kV voltage class.

It was recognized that each application varies in their transient recovery voltages (TRV): For a short line fault, because of the higher surge impedance of the line, the 145kV system will see a higher rate of rise of the recovery voltage, furthermore, since only a single module is proposed for this application the interrupter will be stressed more than in the series combination used at the 362kV level. For a bolted fault the condition reverses, and a higher voltage stress is observed across each interrupter of the 362kV rating.

With this in mind the requirements have been established for the worst case condition, that is, the interrupter must be able to recover to the short line TRV corresponding to 145kV, 100kA and a 450 ohm surge impedance, and for a bolted fault the interrupter must be capable of withstanding a recovery voltage corresponding to approximately 53% of the total recovery voltage of the 362kV system.

A complete tabulation defining the preliminary objectives for the development of the synchronous interrupter is given in Table I.

TABLE I
PRELIMINARY OBJECTIVES

A. Current Ratings

1.	Continuous Current	2000 - 3000 amps
2.	Short Circuit Current	100kA rms
3.	Maximum Symmetrical Interrupting Capability at Minimum Voltage	100kA rms
4.	Short Time Current (1 second)	100kA rms
5.	Momentary Current (10 cycles)	160kA rms
6.	Line Charging Current Switching	500 A rms

TABLE I (Continued)

PRELIMINARY OBJECTIVES

B. Voltage Ratings

1.	Nominal Voltage	182kV (1)
2.	Maximum Rated Voltage	192kV (1)
3.	Bolted Fault TRV (2)	
	a. $E_2 = 338\text{kV}$	
	b. $R = 1.8\text{kV}/\mu\text{s}$	
	c. $T_2 = 294 \mu\text{s}$	
	d. $T_1 = 3.2 \mu\text{s}$	
4.	90% Short Line Fault Rate of
Rise of Recovery Voltage	23kV/ μs

C. Additional Requirements

1.	Rated Frequency	60Hz
2.	Rated Interrupting Time	1 cycle
3.	Reclosing Time	20 cycles
4.	Duty Cycle at Full
Interrupting Rating	CO-15sec-CO
5.	Opening Time
(Synchronous Signal to Contact Part)	1.0 ms
6.	Closing Time	12 cycles
7.	Non Synchronous Interruption shall
not result in a catastrophic failure	

(1) This value of voltage corresponds to:

$$345 \times 0.53 = 182$$

(2) Assume the maximum rated voltage to be 192kV, then

$$E_2 = 192 \times 1.76 = 338\text{kV}$$

1.4 SUMMARY OF CONCLUSIONS

The most significant findings, and conclusions obtained in this project are summarized below:

SENSING

1. The combination of a flux concentrator and an electronic integrating circuit is a viable device that can be utilized for monitoring the main current.

This combination faithfully reproduces the wave form of the main current, under symmetrical or asymmetrical conditions.

2. An electronic current zero detector can provide an accurate prediction for symmetrical currents.

For asymmetrical currents the ratio of the exponential voltage to the AC voltage must be compensated by adjusting a resistor divider.

3. The time variation for asymmetrical currents is in the direction of increasing the arcing time.
4. The small increase in arcing time for asymmetrical currents does not result in any noticeable increase in arc energy input; due to the slower di/dt of the asymmetrical currents.
5. A higher level of confidence is placed in the magnetic synchronous pulse generator, based primarily in the available operating experience.
6. The electronic synchronous pulse generator, compares favorably in all respects, with the exception of field test, to the magnetic synchronous pulse generator.
7. The electronic pulse generator shows a decided advantage over the magnetic device in terms of ease of manufacturing and cost.
8. Both the magnetic and the electronic synchronous pulse generators are suitable devices for the present application.

OPERATING MECHANISMS

9. The electro-magnetic release mechanism appears to be limited in the maximum operating force output and therefore it adversely affects the minimum operating time of an interrupter.
10. The electro-magnetic release mechanism does not operate consistently and large variations in the release time are possible. These time variations have been measured at as much as ± 5 ms.

11. The simplest concept of a mechanism is a pneumatically latched version. A quick latch release is obtained by a direct pulling force, generated by an electrodynamic system, consisting of a repulsion coil and disk. The contact motion is enhanced by means of a pneumatic assist.

VACUUM INTERRUPTERS

12. A Westinghouse vacuum interrupter, Type WL-23340 rated at 12kA and 15kV, can be operated at opening velocities of up to 6 m/sec (20 ft/sec), without any visible mechanical damage.
13. The vacuum interrupter tested with an open gap is capable of withstanding a voltage of 150kV (1-cos wave from and a frequency of 240kHz).
14. A similar vacuum bottle can recover to a maximum voltage of 86.5kV following an interruption near its rating.
15. Using a capacitor discharge, or direct synthetic test method, the vacuum interrupter tested behaved as follows:
$$\begin{aligned} dv/dt &= 16kV/\mu s \quad @ \quad di/dt = 20 \text{ A}/\mu s \\ dv/dt &= 4.8kV/\mu s \quad @ \quad di/dt = 35 \text{ A}/\mu s \end{aligned}$$
16. A vacuum bottle rated 18kA and 15kV (Type WL-23342), when subjected to a direct synthetic test, under the same conditions as before (12kA bottle) exhibited the same dv/dt recovery capability at the same di/dt as the lower rated bottle.
17. The short line fault TRV capability of a vacuum interrupter appears to be independent of the current interrupting rating of the unit; Provided that the interrupter is operated under short arcing time (synchronous) conditions, and the energy input to the arc column does not exceed a limit as defined below.

18. The results suggest that the dv/dt capability of a vacuum interrupter, operated with reduced gap and reduced arcing times, typical of synchronous operation (approx. 1 ms), is:

$$dv/dt \propto (f \cdot i \cdot dt)^{-3.3}$$

19. A performance degradation and the need for a reconditioning process takes place after the vacuum interrupter fails to interrupt at an instantaneous current level that is close to its maximum capability.
20. The performance degradation observed serves to reduce the confidence level of the interrupter and represents a highly undesirable characteristic.
21. The vacuum interrupter, under investigation, when tested using a full synthetic test set-up was unable to recover to any measurable value of dv/dt whenever the di/dt value exceeded 20 A/ μ s.
22. It can be approximated that for a total of 26 A-sec required for this application, the vacuum interrupter will recover to only 200 V/ μ s while the desired value is 6.6kV/ μ s (assumed 4 interrupters in series for this application).

SF₆ INTERRUPTER

23. The maximum interrupting capability obtained with an SF₆ model interrupter having a 19mm (3/4 in) diameter nozzle, and operating synchronously with an upstream pressure of 1.7 megapascals (250 psi) of pure SF₆ was:

$$dv/dt = 0.3kV/\mu s \text{ @ } di/dt = 48 \text{ A}/\mu s$$

24. When a mixture of 50 - 50% (by pressure) of SF₆ and N₂ was used the capability of the interrupter (operated under the same conditions of 23 above) was increased by a factor of 1.3 as follows:

$$dv/dt = 0.39kV/\mu s \text{ @ } di/dt = 48 \text{ A}/\mu s$$

25. An interrupter having a 19mm diameter nozzle and operated at a pressure of 10.3 megapascals (1500 psi) of pure SF₆ can successfully interrupt the following:

$$dv/dt = 4kV/\mu s \quad @ \quad di/dt = 48 A/\mu s$$

26. Assuming that a vacuum interrupter capable of interrupting a current having a di/dt of 48 A/ μ s, and capable of recovering to a dv/dt of several kV/ μ s was available. A ratio in the number of vacuum to liquid SF₆ interrupting modules required for the same voltage rating, based upon the total recovery voltage capabilities of the modules, is 4 to 1.
27. Reduction in the number of operating modules represents a reduction in overall size and cost as well as a reduction in the complexity of the operating mechanisms; Therefore, the SF₆ approach was selected as the direction to be pursued.
28. It was estimated that an interrupter equipped with a 31.75mm (1.25 in) diameter nozzle and operating at 13.8 megapascals (2000 psi) would be capable of interrupting a current having a di/dt of 48 A/ μ s and a maximum dv/dt of 18kV/ μ s.
29. Provided that a minimum dv/dt capability of 10kV/ μ s is obtained, the TRV can be modified using an opening resistor to obtain the required performance.
30. The design of the stationary arcing contact fingers must be re-evaluated and each finger must be strengthened to prevent bending when operating at high pressures (greater than 1500 psi; 10.3 megapascal.)
31. The high pressure volume of the model, appear to be inadequate for supporting the mass flow without having an excessive pressure drop.
32. The temperature rise of the hot spot during continuous current carrying conditions, (3000 Amps), is beyond acceptable limits. It appears to be related to the contact resistance

raised to the 1/5 power. It will be necessary to reduce the contact resistance to approximately $13 \mu\Omega$ to obtain a maximum temperature rise of 65°C .

33. An increase in the number of the contact segments appears necessary in order to reduce the temperature rise. It may also prove necessary to use a material having a higher thermal conductivity or to increase the conductive cross sectional area.
34. The interrupter model as presently designed is fully capable of meeting the momentary current requirement, (10 cycles at 225kA peak) and the short time current requirement of 1 sec at 100kA rms.
35. The predicted interrupting levels of dv/dt and di/dt were not achieved. The maximum performance obtained with a nominal interrupting pressure of 8.3 megapascals (1200 psi) was:
$$dv/dt = 5.5\text{kV}/\mu\text{s} \quad @ \quad di/dt = 40 \text{ A}/\mu\text{s}$$
$$dv/dt = 3.6\text{kV}/\mu\text{s} \quad @ \quad di/dt = 48 \text{ A}/\mu\text{s}$$
36. A possible cause for the low performance of the interrupter is attributed to an excessive pressure drop at the time of interruption.
37. Non synchronous operation of the interrupter at a current level of 40kA rms and at a reduced operating pressure of 1.9 megapascals (275 psi) does not cause excessive deterioration of the contacts. It can be assumed that at higher operating pressures the non synchronous interrupting current can be increased by several kA without jeopardizing the interrupter's integrity.

1.5 RECOMMENDATIONS

It is firmly believed that the use of high pressure (Liquid) SF_6 as the arc quenching media shall result in an overall reduction in the size of an interrupter and the number of interrupter modules required for a given circuit breaker rating. However, it should be noted that the possibility of using vacuum interrupters in the future is not precluded. As the vacuum interruption technology develops it may be possible to obtain interrupters having a higher voltage rating as well as a higher interrupting rating. When such interrupters become available a re-evaluation of their synchronous capability will be advisable.

The exploratory tests that have been carried out in the present project served to provide encouragement for the liquid SF_6 approach; But at the same time many questions have been raised that remain unanswered.

To fully demonstrate the capabilities of liquid SF_6 interrupters, and to make use of these findings the following is recommended:

1. Perform studies of the flow characteristics of liquid SF_6 . Analytical as well as experimental approaches should be taken to determine pressure gradients, and mass flow. It is also desirable that the physical state; liquid, solid or gaseous at the throat of the nozzle be observed under transient flow conditions.
2. The criticality of the arcing time that has been observed should be further investigated to determine any relationship that may exist with some of the pressure oscillations recorded during testing.
3. Optimize the available model interrupter and explore the maximum limits of performance.
4. Continue the development of a Synchronous Transmission Interrupter that can be used in a modular form to accommodate a wide range of currents as well as voltages.

The possibility of using the interrupter at different operating pressures to accommodate variations of the interrupting current requirements should be thoroughly investigated.

5. Pursue the design and demonstrate the feasibility of assembling a series of modules to accommodate all voltage ratings from 145kV up to 1200kV RMS.
6. Explore further the capability of the interrupter when operated non-synchronously.

PART II

PHASE I

2.1 BASIC CONCEPT OF SYNCHRONOUS BREAKER

Theoretically a synchronous interrupter will be a device that changes instantaneously from a perfect conductor to a perfect insulator. This change of state must take place at the time where the alternating current reaches its natural zero value. For a mechanical device it constitutes a physical impossibility, since a finite contact gap must be developed in practically zero time. However, it is possible to design a quasi synchronous interrupter; that is, one that will part its contacts at a predetermined short time ahead of current zero. This time is generally in the order of a few tenths of a millisecond, and therefore, a high opening speed is needed in order to develop a contact gap large enough to withstand the transient recovery voltage that ensues after current interruption.

The necessity for a high opening velocity dictates that the contact mass must be reduced as much as possible or, the required operating forces can become excessively large. Since the mass of the contacts, to a certain extent, controls the maximum continuous current and the making current capability of the interrupter, it becomes necessary to separate the interrupting function from the continuous and the making current functions.

For the continuous current function a set of main contacts, that will open prior to the parting of the arcing contact, can be designed. This set of contacts can be dimensioned with a sufficient mass, contact pressure, and number of contact points, to achieve continuous current ratings of 2000 and 3000 amperes.

To avoid the necessity of a massive interrupting contact capable of meeting the making current requirements, it is envisioned that the design will incorporate an isolating or disconnecting break in series with the interrupting break.

The isolating break will have full current capability as well as the making capability. In addition to the current ratings this isolating break will provide dielectric isolation and it will be capable of withstanding the full BIL rating, thus relieving the interrupter from this requirement.

The isolating break will be operated sequentially with the interrupter break as follows:

During opening a trip signal will be given to the interrupting break. At approximately three cycles, after interruption has taken place, the isolating break will be opened. The interrupting break will then be closed at approximately 10 milliseconds after the opening of the isolating break has been successfully completed.

The circuit breaker closing function is assigned to the isolating break and therefore the closing signal will only be given to the isolating break. In the event that an instantaneous trip is required the interrupting break can be opened at any instant of time. The trip free requirement is inherently fulfilled because separate mechanisms, electrically interlocked to each other, are used for the interrupting and the isolating break.

Another function of the isolating break, when used together with an SF₆ interrupter, will be to allow the interrupting break to be reset and resurized for instantaneous tripping as it is required in a CO and a standard duty cycle (CO-15sec-CO).

The concept, that has just been described, for a circuit breaker to be operated quasi synchronously, requires the development of at least four sub assemblies or main components.

- a) A current zero detector and trip signal generator.
- b) A high speed operating mechanism.
- c) An interrupter, and
- d) An isolating break.

2.2 CURRENT ZERO DETECTION

One of the basic necessities for a synchronous circuit breaker is a device capable of predicting the precise time of the natural current zero regardless of the current magnitude and the degree of asymmetry.

After the prediction of the upcoming current zero is made the signal is processed, and changed to a form suitable to be used as a tripping command.

In general the system must be able to accurately detect the flow of current and to predict the advent of a current zero. The prediction time of the current zero must be adjustable between some arbitrary limits of, let us say, 3 ms and 0.5 ms.

The complete device will consist of:

- a) Sensor
- b) Phase Shifter
- c) Pulse Shaping
- d) Output Signal

The complete assembly can be either all electromechanical, all electronic, or hybrids made up of magnetic and electronic components.

2.2.1 SENSOR

The sensing or monitoring of the current flow can be accomplished by using readily available devices such as: current transformers, and linear couplers. However, the use of a current transformer is questionable because there is no need for the large output signal that is standard with C.T's; furthermore, the units are large and relatively expensive. They can saturate and therefore deform the shape of the current wave that is being monitored.

Problems caused by saturation can be avoided by the use of linear couplers. Nevertheless, these devices are also large and expensive.

The application of semiconductors could also be investigated and devices such as a Hall generator or a Magnistor (Reference 1) could be used for this application. The output of these semiconductors will be proportional to the magnetic flux (B) and the magnetic field (H) respectively. These devices

have output signals that are low level and low energy; therefore, these signals are prone to be affected by noise. Moreover, they require additional amplification and individual power supplies.

Another alternative, and probably the most promising of all, is the use of flux concentrators. A properly designed flux concentrator will not saturate at the higher current amplitudes, and its output signal can be adequately tailored to be suitable as input signal to a phase shifter.

FLUX CONCENTRATOR DESIGN AND TESTS

To demonstrate the feasibility of using a flux concentrator as the main current detection device a design, described below, was tested.

The graphical concept of a flux concentrator is shown in Figure 1.

FIGURE 1 - GRAPHICAL CONCEPT OF FLUX CONCENTRATOR

From basic theory it follows that, (referring to Figure 1).

$$e_2 = N \frac{d\phi_c}{dt} \quad (1)$$

$$\phi_1 = BA \quad (2)$$

$$B = \mu_o H = \mu_o \frac{i}{2\pi r} \quad (3)$$

Substituting 3 into 2:

$$\phi_1 = \mu_o \frac{i}{2\pi r} A \quad (4)$$

Since the flux inside the concentrator is equal to a constant times the outside flux,

$$\phi_c = K\phi_1 \quad (5)$$

Substituting ϕ_c for ϕ_1 we have

$$\phi_c = KA\mu_o \frac{i}{2\pi r} \quad (6)$$

Differentiating equation (6) with respect to time

$$\frac{d\phi_c}{dt} = KA\mu_o \frac{1}{2\pi r} \frac{di}{dt} \quad (7)$$

Substituting 7 into 1

$$e_2 = NKA\mu_o \frac{1}{2\pi r} \frac{di}{dt} \quad (8)$$

From Equation 8 it readily follows that in order to obtain a voltage (E) proportional to the current (i) the output of the flux concentrator must be integrated.

The integration can be readily accomplished if an operational amplifier and an RC combination is used in the form of a standard integrating circuit. Figure 2.

FIGURE 2 - STANDARD INTEGRATING CIRCUIT

Referring to this figure it is seen that the output E is:

$$E \approx - \frac{1}{j\omega RC} e_2$$

And therefore, E is 90° out of phase with respect to e_2 . The amplitude of E can be made equal to the amplitude of e_2 by proper selection of R and C since

$$E = e_2 \text{ when } \omega RC = 1$$

Verification of the concept was provided by tests performed on a model flux concentrator.

The model was constructed with the following specifications.

- minimum sensing current 4kA rms
- maximum sensing current 225kA peak
- minimum output voltage 4 volts rms

CORE DESIGN (Figure 3)

Material	-	Silicon Oriented Steel Type M6
Dimensions	-	Length 23 cm, (9 in)
		Width 5 cm, (2 in)
		Height 5 cm, (2 in)
Winding	-	Number of turns = 500
		Wire size = 28 AWG.
		Wire resistance = 0.00215 Ω /cm (0.0655 Ω /ft)
		Wire length = 104 m, (340 ft)
		Resistance Winding = 22.4 Ω
		Self Inductance of coil = 3.8 mH.

FIGURE 3 - MODEL OF FLUX CONCENTRATOR

FIGURE 4 - COMPARISONS OF
OUTPUT OF CURRENT
TRANSFORMER AND
OUTPUT FROM FLUX
CONCENTRATOR

TIME = 5 ms/DIV
FC = 5 VOLTS/DIV
CT = 10 VOLTS/DIV

FIGURE 5

TIME = 10 ms/DIV
FC = 5 VOLTS/DIV
CT = 10 VOLTS/DIV

FIGURE 6

TIME = 2 ms/DIV
FC = 5 VOLTS/DIV
CT = 10 VOLTS/DIV

TEST PROCEDURE AND RESULTS

The test performed on the model flux concentrator consisted of measurements of the voltage output and comparison of the wave form to the original current.

The main current was measured by means of a current transformer. The output of the transformer was recorded using a tektronix oscilloscope (Model 564); a second trace in the oscilloscope record was the output of the flux concentrator. (Figures 4, 5, 6)

In the calculations it was assumed that the main current was flowing through a circular conductor. The conductor used for testing was a flat copper bus 10 cm, (4 in) wide and 13mm, (0.5 in) thick. It was assumed that the conductor shape will influence the magnetic flux distribution, and thus, result in an output signal, from the flux concentrator, that depends upon the orientation of the bus and the concentrator.

To verify this assumption measurements were made with the flux concentrator at two positions 90° apart of each other; measurements were made at both positions and at distances of 13, 25 and 64 cm from the center of the conductor.

From the data obtained it was possible to verify the expected change in signal output relative to the location of the flux concentrator and to the bus; It was also possible to determine the relationship between the concentration factor (K) and the distance away from the conductor.

The relationship between K and the distance as well as the location between the flux concentrator and the conductor is shown in Figure 7.

Referring to this figure it can be seen that the measured points at 13 cm, (5 inches) away from the conductor have been ignored; the omitting of these points is justified since due to the shape of the conductor an elliptical configuration is expected for the magnetic field, and therefore, some of the flux lines will penetrate the concentrator at locations other than the ends. As the radial distance from the conductor is increased the leakage flux in the concentrator will be reduced and the results will be more consistent.

FIGURE 7 - DISTANCE FROM CONDUCTOR (d) VS. CONCENTRATOR FACTOR K

In conclusion it can be stated that a flux concentrator is a viable device that can be utilized for monitoring the main current. The test have indicated that the output voltage obtained from a flux concentrator and an integrator faithfully reproduces the main current under symmetrical or asymmetrical conditions.

2.2.2 PHASE SHIFTING AND PULSE SHAPING

Once the main, or primary, current has been measured, and its wave shape reproduced as a secondary current; it is possible to estimate the next current zero crossing by either: advancing, in time, the secondary current with respect to the primary current, or by cancelling a biasing flux in a flux shifting device, and then balancing the magnetic force created by the secondary current, and the mechanical force produced by the operating mechanism.

At the initiation of the project a proven design of a synchronous pulse generator was available; Nevertheless, it was judged that it would be desirable to explore the possibility of developing alternate designs, that could compare favorably to the existing device.

The existing synchronous pulse generator (SPG) is a device presently being used in a field application and has been fully described in Reference 2.

Two designs have been investigated in this project:

- 1) Electronic pulse generator and
- 2) Electromagnetic release mechanism

ELECTRONIC SYNCHRONOUS PULSE GENERATOR

The electronic synchronous pulse generator is a basic application of a filtering circuit and a summing operational amplifier. Additional operational amplifiers are used for the purpose of shaping the pulse and providing a usable signal output. A schematic diagram of the circuit is shown in Figure 8.

FIGURE 8 - ELECTRONIC SYNCHRONOUS PULSE GENERATOR CIRCUIT

The input signal is applied to a combination bandpass filter and voltage divider. The dc component of current, found in an asymmetrical current, flows through the inductor (L) and the series resistance made up of R_1 and R_2 . The 60Hz sinusoidal current flows through the capacitor C_1 and the series resistor R_2 . The voltage drop appearing across R_2 is then clipped and subsequently amplified, clipped once more and finally amplified and differentiated.

As it is readily seen, the 60Hz signal is advanced in time with respect to the input signal by virtue of capacitor C_1 . Since generally the dc component has a slow rate of decay, it is difficult to properly phase shift this signal and therefore only an approximation of the magnitude of this voltage at a certain time in the future can be made. This approximation is accomplished by means of the voltage divider made up of R_1 and R_2 .

The purpose of the first clipping stage is to enable the instrument to accommodate a greater range of signals, and therefore a wider range of primary currents. The clipping level is at the nominal cut off of a silicon diode or 0.6 volts. The signal is then amplified approximately 20 times to a value of 12 volts and clipped again this time to obtain an approximate square wave. Once the square wave has been amplified to approximately 12 times. Its derivative is obtained by means of a simple RC differentiating circuit, the output of which is a sharp voltage pulse as shown in Figure 9.

TIME = 5 ms/DIV
INPUT = 5 VOLTS/DIV
OUTPUT = 5 VOLTS/DIV

FIGURE 9 - COMPARISON OF INPUT AND OUTPUT SIGNALS
FOR CIRCUIT SHOWN IN FIGURE 8

The size of the components needed for the input filter section can be calculated using the following relationships:

$$\text{Let } Z_{(\text{Total})} = \sqrt{Z_O^2 + R_2^2}$$

$$Z_O^2 = (X_C)^2 \frac{R_1^2 + X_L^2}{R_1^2 + (X_L - X_C)^2}$$

$$X_C = \frac{2X_L Z_O^2}{2(Z_O^2 - R_1^2 - X_L^2) \pm \sqrt{(2X_L Z_O^2)^2 - 4(Z_O^2 - R_1^2 - X_L^2) Z_O^2 (R_1^2 + X_L^2)}}$$

The tests performed on a model device indicated that a fairly accurate time prediction can be obtained for symmetrical currents. For the asymmetrical currents it becomes necessary to compensate the ratio of the exponential voltage division. This compensation was made by increasing the value of R_1 . It was found that for an $\frac{X}{R}$ ratio of 15 the dc portion of the signal should be reduced to approximately 95%. These compensations must be made independently for each value of $\frac{X}{R}$.

It was also observed that because of the initial faster rate of decay of the exponential voltage there was a variation in time, in the pulse output, between the first and second loops of current. However, it is unlikely that the breaker will be required to open within the first half cycle of a fully offset fault.

Moreover, the time variation is in the direction of increasing the arcing time; but, because of the asymmetry, the rate of change of current (di/dt) as well as the instantaneous value of current at the time of contact part are reduced, and therefore the increased arcing time does not result in any significant increase in arc energy input to the interrupter.

ELECTRO-MAGNETIC RELEASE MECHANISM

The sensors, previously described, serve only to predict the upcoming current zero, and to give an electric signal which is used as the trip command. Additional sources of energy are then needed to unlatch, or initiate, the motion of the contacts.

The concept of an electro-magnetic release mechanism attempts to incorporate into a single device the two individual functions of prediction and tripping.

The design, (Figure 10), consists of:

FIGURE 10 - ELECTRO-MAGNETIC RELEASE MECHANISM

An Alnico 5 DG permanent magnet (A); two "C" shaped cores, (B and C), made of Silectron transformer steel; a cast steel bridge, or magnetic latch, (E); and two coils, S_B and S_C , located on cores B and C, respectively.

The magnetic force produced by the permanent magnet A, and represented as F_A in Figure 11, is used as the latching force. The force F, also in Figure 11,

represents the opening force being exerted by the contacts upon the latch; it follows then that in order to maintain the contacts in the latched position it is necessary that

$$F_A > F$$

FIGURE 11 - FORCE DIAGRAM FOR ELECTRO-MAGNETIC RELEASE

A signal (I) proportional to the primary current is applied to coil S_B and therefore a magnetic flux, proportional to the current and the number of turns in the coil, is induced in core B. This flux in turn develops a force F_B across the bridge E.

Force F_B is in the same direction as F_A and therefore the total force holding the bridge E is the sum of F_A and F_B .

When it becomes necessary to open the contacts, a trip signal is given to the release mechanism. The trip signal takes the form of a dc voltage that is applied to coil S_C . A flux, proportional to the magnitude of the trip current and the number of turns of coil S_C is established in core C. This flux is calculated so that it will be equal and opposite to the flux producing the force F_A , and therefore, F_A is cancelled by force F_C resulting from the trip signal. The force F_B is then acting alone to oppose the opening force F , and as shown in Figure 11, F_B is decreasing as the current I approaches zero. It follows then that at some time prior to current zero the magnitude of F_B is less than the magnitude of F and therefore the bridge E is released and the contacts begin to open.

The time advance of tripping can be controlled by means of phase shifting of the current I with respect to the primary current, or by controlling the cross over point of forces F_B and F .

The release time is expected to be consistent whenever the currents are symmetrical; However, when asymmetrical currents are encountered some time variations are expected. The variations in the release time, relative to current zero, will increase the total arcing time; Nevertheless, since the rate of change of current is reduced, the total energy input does not show any appreciable increase, and therefore, the additional arcing time will be perfectly acceptable.

To verify the operating principles and the repeatability of the results a series of tests were performed where the forces F , F_A , F_B and F_C were investigated.

The results obtained in the tests indicated that:

- 1) *A high level of leakage fluxes exist in the design and only a portion of the fluxes induced in core A appear across the bridge E.*
- 2) *The maximum holding force obtained for the design tested was 179 lbs.*
- 3) *There is a considerable time variation in the release of the bridge. This time variation can possibly be attributed to the uncertainty of the starting point in the hysteresis loop of the material.*

2.2.3 EVALUATION OF SENSOR'S PERFORMANCE

Table II shows a comparison of the relative advantages, and disadvantages, as well as a confidence factor for each device. The numerical factor describing the comparative confidence ranking of each sensor indicates that the confidence level increases as the factor decreases. The factor's value is a weighted number representing the product of the criticality factors for the categories listed below.

Design Experience

Considerably different from existing hardware	1.2
Similar to existing hardware	1.0
Same as existing hardware	0.8

Ease of monitoring performance

Difficult	1.3
Reasonably easy	1.0
Very easy	0.7

Likelihood of failure

Definite	1.5
Very possible	1.0
Remote	0.5

CONCLUSIONS

A higher level of confidence is placed in the magnetic synchronous pulse generator, based primarily in the operating experience available.

The electronic synchronous pulse generator has not been field tested; But nevertheless, it compares favorably in all other respects to the magnetic device. It shows a decided advantage in terms of ease of manufacturing and cost.

The electro magnetic release mechanism appears to be limited in the maximum operating force and therefore in the minimum operating time. The device does not operate consistently and large variations in the release time, prior to current zero has been observed. These time variations have been measured as ± 5 ms.

RECOMMENDATIONS

Both the magnetic and the electronic synchronous pulse generators are suitable devices for the present application; However, since it is highly desirable to have alternate methods of current zero detection and to provide

TABLE II

TABULATED COMPARISON OF SENSORS

DEVICE	ADVANTAGES	DISADVANTAGES	CRITICALITY FACTOR
Synchronous pulse generator (Magnetic)	<ol style="list-style-type: none"> 1. Does not require a separate sensor 2. Self contained device 3. Less sensitive to transients 4. Rugged construction 5. Field proven performance 	<ol style="list-style-type: none"> 1. Low level signal 2. Requires amplification and shaping of the signal 3. Sensitive to leakage current flow 4. Relatively difficult to manufacture 5. Requires single dc power supply 	0.8
Electronic	<ol style="list-style-type: none"> 1. Signal can be tailored to needs very easily 2. Wider adjusting range for currents 3. Better accuracy of prediction 	<ol style="list-style-type: none"> 1. More sensitive to transients 2. Requires separate sensing device 3. Requires a double ended dc power supply 	1.0
Electro Mechanical Release	<ol style="list-style-type: none"> 1. No electronic equipment needed 2. No additional power supplies for tripping the breaker 3. Self contained operator 4. Insensitive to transients 	<ol style="list-style-type: none"> 1. Limited operating force 2. Possible deterioration of permanent magnets 3. Continuous biasing current to stabilize time variations 4. Slower operating times. 5. Sensitive to magnetic fields 	2.4

the opportunity of gaining field application experience it is recommended that the electronic synchronous pulse generator be chosen as the device to be used in conjunction with future synchronous breaker prototypes.

2.3 OPERATING MECHANISM DEVELOPMENT

The specific requirements for an operating mechanism are dependent upon the contact configuration and the interrupting media that is used. This dependence is clearly illustrated when the contact mass, and the opening velocities of vacuum and SF₆ interrupters are compared.

In a synchronous circuit breaker utilizing a vacuum interrupter it is expected that the opening velocities will be limited to a maximum of 8 m/sec (26 ft/sec) and therefore, the possibility exists of using a relatively simple mechanism having either a spring or a pneumatic driving force.

The requirements for the opening velocity are considerably increased for an SF₆ interrupter; Where it is desired to obtain opening velocities of approximately 24 m/sec, (80 ft/sec). These high velocities suggest the need for a mechanism capable of developing high rates of acceleration, and subsequently requiring a rather large driving force.

Regardless of the interrupting medium, a common requirement for the interrupters is that of a fast latch release which is necessary to minimize the total contact parting time as well as the total interrupting time.

From past experience, References 2 and 3, it has been established that the preferred method for initiating the opening operation of a synchronous circuit breaker is by utilizing the concept of an electrodynamic drive.

The principles of operation of such drive mechanisms are fairly well known and have been extensively studied elsewhere (References 2, 3, 4, 5, 6).

A mechanism model for a vacuum interrupter and three different concepts of mechanisms for SF₆ interrupter were designed and tested.

Following is a description of each mechanism and a summary of the test results.

2.3.1 MECHANISM FOR VACUUM INTERRUPTER

It was stated previously that a relatively simple mechanism could be used for operating a vacuum interrupter.

The simplicity of the mechanism is increased even more when a single vacuum interrupter is utilized, as it was the case in the initial investigations of this program. In the future, should vacuum be chosen as the interrupter media, it is likely that multiple interrupters connected in series will be used: In which case the basic mechanism utilized for a single interrupter could be modified to satisfy the operating requirements of multiple interrupters.

The initial design, shown in Figure 12, consisted of a supporting structure, that also served as a test stand for current interruption tests. Three horizontal plates were attached to the supporting frame. The vacuum interrupter, was mounted on the top plate; However, for the initial test of the mechanism only a mock up contact, (shown in Figure 12), was used. The middle plate supported a repulsion coil and a neoprene bumper, or shock absorber, mounted on the bottom plate.

The repulsion disk, part of the electrodynamic drive, was attached directly to the contact stem, and therefore, the contact was opened by a straight pulling force generated by the electrodynamic drive.

When the driving energy is supplied in the form just described it must be realized that the system is rather inefficient. Basic studies of electrodynamic drive systems have demonstrated that the maximum efficiency is obtained when the disk and the coil are closely coupled. In the mechanism design being discussed, the coupling is at a maximum only briefly since as the current magnitude is increasing in the coil, the disk is moving away; thus, creating a condition where only a small portion of the energy is being transferred to the moving member. Operation of a mechanism in this fashion requires large amounts of stored energy to provide the necessary initial acceleration needed to achieve the specified opening velocities. Obviously the large initial acceleration represents large impulsive forces that could overstress the moving parts.

FIGURE 12 - OPERATING MECHANISM FOR VACUUM INTERRUPTER

Despite the disadvantage just mentioned this mechanism constitutes the simplest possible design and therefore its capabilities and limitations were investigated in a series of tests.

During the tests, the input energy to the repulsion coil was varied by changing the capacitance and/or the charge voltage of the power supply. The available capacitance was from 120 to 600 μf in multiples of 120 μf ; while the charge voltage was adjustable in the range of 1800 to 3000 volts.

Measurements of the opening velocity were obtained by means of a slide resistance type travel recorder. In addition to the travel recorder the opening velocity, the latching operation, and the bumper action were observed with the aid of high speed movies. It was possible to establish a very good correlation of the opening velocity for the two methods of measurement, and it was considered that either method could be used in future testing.

The results indicated that the contact velocity, over the first 6mm (1/4 in) of travel, is directly proportional to the energy input; changes in the capacitance or the voltage charge affect the operating velocity only when taken as a product, that is, when expressed in terms of total stored energy.

The changes in frequency of discharge or current magnitude that result from variations of the capacitance or voltage parameters are not significant in the short periods of time, and travel that were investigated; Therefore, no significant effect of either parameter individually is noticed.

The relationship between the travel velocity and the energy input is shown graphically in Figure 13, and it can be represented mathematically as:

$$V_c = 0.66 \times 10^{-2} E_o - 0.52 \text{ (m/s)}$$

where V_c = average opening or travel velocity over the first

(1/4 inch of travel in ft/sec)

(6.35mm of travel in m/sec)

E_o = energy input to the electrodynamic drive ($1/2 CE^2$)
in Joules

FIGURE 13 - ENERGY INPUT (TO IMPULSE COIL) VS. TRAVEL VELOCITY

This series of tests served to verify our conviction that this method of accelerating the contact is rather inefficient, and that the demands on structural strength of the moving members are unnecessarily high.

To satisfy these strength requirements, it is necessary to reinforce the parts; thus, making them heavier and increasing the magnitude of the accelerating force required to produce the same velocity.

The maximum velocity obtained with this interrupter was 6 m/sec, (19 ft/sec), with an energy input of 960 Joules. An increase of energy resulted in the destruction of the repulsion disk and some damage to the mock contact.

It was evident that the accelerating forces should be constant and distributed over a larger period of time. This requirement can be met by adding a pneumatic drive to the mechanism. The electrodynamic drive will then be used only to open a valve and therefore the total energy input will be greatly reduced.

A design incorporating this driving system is shown in Figure 14. In this design a pressurized cylinder and a piston were added between the shaft of the mocked up contact and the repulsion disk. The upper edge of the piston acts as a high pressure seal. The piston is maintained in the closed position by virtue of the force resulting from the area differentials designed into the piston.

The opening operation is initiated by discharging the stored energy into the electrodynamic drive, and consequently opening the piston seal; Once the seal is broken the pressurized gas, contained in the cylinder, will fill up the space above the piston top surface forcing the piston down.

The volume in top of the piston surface was deliberately kept small in comparison with the total gas volume, and therefore, no appreciable drop in pressure (approximately 10%) will result from the expansion in volume that takes place when the unit is operated.

FIGURE 14 - OPERATING MECHANISM FOR VACUUM INTERRUPTER
UTILIZING PRESSURE ASSIST CYLINDER

The travel velocity can be controlled by varying the operating pressure. Theoretical calculations relating the velocity and the pressure yielded the following relationship:

$$V_c = 3.24 \times 10^{-3} p^{0.5}$$

where V_c = travel velocity in m/sec

P = operating pressure in pascals

This relationship was derived under the assumptions that the contributions due to the friction forces, the reaction from the rubber bumper, and the acceleration produced by the impulse coil, (after the motion has been initiated), are negligibly small compared to the contribution of the driving pneumatic force.

Tests were performed on a model mechanism under the same testing conditions previously used for the first model tested. The results of the test are graphically shown in Figure 15. It is seen from this curve that the velocity, as it was predicted, varies as an exponential function of the pressure.

$$V_c = 8.47 \times 10^{-3} p^{0.44}$$

It is also seen that the constant term obtained from the experiments is larger than the calculated one, this implies that the initial acceleration and the simulated contact's holding force are not negligible as it was originally assumed.

The mechanism demonstrated that an opening velocity of 6 m/sec (corresponding to a 6.4mm contact gap at 1 ms), can be obtained using a pneumatic pressure of 3.1 megapascals. The input required by the repulsion coil was 240 μ f at 2200 volts. This energy input is indeed much lower than what is required when no pneumatic assist is provided.

This model of operating mechanism was used in conjunction with vacuum interrupter for the remainder of this project.

FIGURE 15 - OPERATING PRESSURE VS. AVERAGE OPENING VELOCITY DURING FIRST 6mm OF TRAVEL

2.3.2 MECHANISM FOR SF₆ INTERRUPTER

The two main requirements for an operating mechanism used in conjunction with an SF₆ interrupter are:

1. A maximum time of one millisecond for contact part, and,
2. An average opening velocity of 24 meters per second, (80 ft/sec) for the first 25mm (1 inch) of travel, after contact part.

The operating mechanism as a whole comprises; a latch system, a latch release, and a driving mechanism.

The choice of a latch release system has been made in favor of an electrodynamic drive, based on the experience accumulated in the past and in the adaptability of the concept to various mechanisms schemes. As it was previously stated the electrodynamic drive is the most desirable way for producing an impulse force that will impart the initial acceleration required to the motion of the contacts.

LATCH SYSTEMS AND DRIVE MECHANISM

Since the SF₆ interrupter envisioned for this project is one that operates in a two pressure system, and utilizes the interrupting contact as a blast valve assembly; the use of the gas pressure as the contact driving force becomes a logical choice.

Obviously the interrupting requirements will dictate the operating pressures as well as the physical design of the interrupter. Nevertheless, and because the interrupting contact is also to be used as a member of the operating mechanism some of its dimensions will be controlled by the forces required to produce the desired rates of acceleration.

Prior to the initiation of motion, the proper dimensioning of differential areas in the moving contact, or piston, provide means for either holding the contacts close or for driving the contacts open. As the contact latch is released the blast valve seal is broken and the high pressure acts over the entire face of the contact; thus, producing a driving force that can be easily controlled by means of the operating pressure and the area of the piston.

In all of the models of the mechanisms tested the interrupter gas pressure was used as the driving force. The methods for maintaining the contacts closed, (the latching system), represented the main difference on each of the mechanisms designed. Some mechanisms were tested on the basis of a single interrupter while another mechanism was tested with two interrupters in series. Those mechanisms that employed a single interrupter were investigated on basis of the need for such design for the lower voltage class breaker (145kV) and because it is conceivable that the design can be easily modified to accommodate the use of several interrupters in series.

The three latching concepts investigated were:

- 1) Hydraulic latch
- 2) Mechanical latch
- 3) Pneumatic latch

Discussion of the tests results and descriptions of each concept are given below.

HYDRAULIC LATCH MECHANISM

A schematic outline of the hydraulic mechanism is shown in Figure 16. For this mechanism the driving force is derived from the interrupter's operating gas pressure acting on the piston surface constituted by the interrupter contact. The interrupting contact for the hydraulically latched mechanism is designed in a way such that an opening bias force of approximately 8450 Newtons (1900 lbs) is continuously available trying to open the contacts. This opening force is opposed by a hydraulic pressure of 2.46×10^{-7} Pascals (3570 psig) acting on a piston with a surface area of 5 cm^2 (0.785 in^2); Thus, resulting in a net sealing or latching force of:

$$12300 - 8450 = 3850 \text{ Newtons}$$

FIGURE 16 - SCHEMATIC DIAGRAM OF
HYDRAULIC LATCH SYSTEM

The following assumptions for the original design were used:

Moving contact mass = $M_c = 0.3 \text{ Kgm}$

Mass of oil in driving cylinder = $M_d = 0.081 \text{ Kgm}$

Mass of oil in valve area = $M_v = 0.045 \text{ Kgm}$

Acceleration of contact = $a_c = 25000 \text{ m/sec}^2$

Acceleration of oil = $a_d = 25000 \text{ m/sec}^2$

$a_v = 14000 \text{ m/sec}^2$

The resulting accelerating forces then are:

contact = $F_c = 7500 \text{ Newtons}$

oil = $F_o = 2655 \text{ Newtons}$

If a constant friction force of 1400 Newtons is assumed then the total driving force becomes

$$F_T = 11555 \text{ Newtons (2600 lbs)}$$

As it can be seen from the above assumptions the effect of the hydraulic oil upon the forces required can not be neglected and therefore the total mass of oil must be minimized. However, even when the hydraulic dump valve is located close to the contact to avoid long hydraulic lines, there is still a sizable length of line from the valve to the hydraulic reservoir which is normally located at ground potential.

One possible solution for this problem consist in designing a valve, shown in Figure 17, where an intermediate volume was provided to minimize the operating times.

FIGURE 17 - HYDRAULIC VALVE FOR FAST PRESSURE RELEASE

Referring to Figure 17, the valve consists of operating cylinders 1 and 2 and the operating pistons 3 and 4, these pistons are directly connected to the interrupter contacts. A volume, item 5, is connected to the hydraulic accumulator and is maintained at high pressure. The intermediate volume, 7, is always connected to an oil reservoir through line 6. The pushrod, 8, is connected to the repulsion disc of an electrodynamic drive system.

With the breaker closed the valve is in the position shown in the left side of Figure 17. The volumes 1 and 2 are pressurized and pistons 3 and 4 keep providing the necessary force to keep the breaker contacts closed.

To open the contacts the impulse coil is energized to push rod 8 upwards. The washer seal 9 seals the connection from volume 15 to the reservoir and the valve's body 10 is pushed up against the forces caused by the differential area, 17, and the spring, 11. The seals 18 and 19 are opened and volume 15 is pressurized through the orifices, 13. This high pressure now in volume 15 pushes the valve's body. When seal 18 is open, the pressure in cylinders 1 and 2 is released into volume 7 which is connected to the reservoir. Volume 7 is normally vented to atmosphere through hole 12 and is dimensioned to accept the displaced oil from cylinders 1 and 2. After a period of time, which is much longer than the contact opening time, volume 7 will be equalized with the reservoir.

After the contacts have been opened the valve is in the position shown in the right hand side of Figure 17. Cylinders 1 and 2 and volume 15 are depressurized.

The successful performance of the hydraulically latched mechanism depended very heavily on the proper operation of the valve just described.

A full scale model of this mechanism was fabricated and operating tests were performed. The tests served to demonstrate that a good series seal such as required by seals 18 and 19 is a very difficult task, and that this area of the design should be modified. The results also indicated that a fluctuating pressure can be generated which causes the body of the valve to oscillate and relieve the pressure intermittently. This condition was not remedied and the tests were suspended when it became evident that to obtain a proper seal an

increase in the force of the biasing spring, 11, was required. This increase in force to 4000 Newtons (900 lbs) was judged unacceptable because the energy input to the electrodynamic drive would have to be increased considerably to obtain the required contact parting time.

Furthermore, it became evident that a great deal of reluctance existed, among those experienced in the circuit breaker art, for accepting a mechanism that does not have an option of the fail safe mode of operation. The primary disadvantage of this design is the mode of failure; Should the hydraulic pressure be lost, the contacts will immediately open.

A second disadvantage of this mechanism is the introduction of the hydraulic oil into the general area of the contacts, the possibility of small leaks can not be ruled out and therefore it will be possible to contaminate the SF_6 with hydraulic oil.

One advantage that can be obtained from a hydraulic mechanism is that the insulating operating link between the interrupters located at line potential and the operating controls at ground potential is inherently provided by the oil column. A second advantage constitutes the simplicity of the design for the operation of multiple interrupters.

The hydraulic mechanism approach then was ruled unacceptable and all investigations were terminated.

MECHANICALLY LATCHED MECHANISM

A number of designs for mechanical latches, used for holding the contacts of an interrupter in the closed position, have been utilized in the past by the circuit breaker industry. However, in most of these concepts the time needed for releasing the latch is at least one order of magnitude higher than the release time required for a synchronous operation of an SF_6 interrupter, (approximately 0.25 ms).

A design of a quick releasing latch was conceived and the concept is illustrated in Figure 18. The left side of the figure shows the contact closed and latched. The right hand side shows the latch in the released position and consequently the interrupter contacts are open.

FIGURE 18 - BALL RELEASE MECHANICAL LATCH

The mechanism consists of an insulating operating rod, 1. The upper end of this rod serves as a keeper for several steel balls, 2, distributed circumferentially around the lower end of the contact, 4.

A set of pre-loaded Bellevue washer springs, 3, exerts force on the latching balls. This spring force is intended to provide the initial acceleration for opening the contacts.

The opening of the contacts is initiated by energizing the repulsion coil of an electrodynamic drive. The repulsion force generated displaces the operating rod 1, upwards and releases the latching balls. The opening spring initiates the motion of the contacts and after the gas seal, 7, is broken the high pressure gas provides the necessary pneumatic assist. Closing of the contacts is accomplished by admitting high pressure gas to the underside of piston 5. This piston moves upwards driving the contacts closed and charging the springs 3 and 6. As the latching balls line up with the respective slots they are driven into position by the resetting force of rod 1. This resetting force is provided by a spring that is installed at the lower end of the rod.

After the mechanism is latched the resetting high pressure is released and the closing piston 5 returns to its normal position, driven by the force of spring 6.

The following assumptions were used for calculating the results shown in Figure 19.

contact mass = $M_c = 0.5 \text{ Kgm}$

friction forces = $F_f = 560 \text{ Newtons}$

kicker spring force = $F_s = 6800 \text{ Newtons over a length of } 1.5 \text{ cm}$

Pneumatic forces acting on the contact = 7950 Newtons
(for $\Delta p = 1.52 \times 10^6 \text{ pascals}$)

A model of this mechanism was tested to determine its operating characteristics. The contact speed was measured at operating pressures in the range of 3.5×10^5 to 2×10^6 Pascals (50 to 300 psi).

FIGURE 19 - ACCELERATION VS. CONTACT STROKE

Two energy levels, 125 and 250 Joules, were used initially as inputs to the electrodynamic drive. The lower energy level resulted in relatively long contact parting times and therefore the higher level was selected for the final tests.

The results obtained are shown graphically in Figure 20. It can be observed from this figure that the contact parting time and the average opening velocity obtained do not meet the established requirements:

	<u>Measured</u>	<u>Required</u>
Contact part time	1.6 ms	0.8 - 1 ms
Full gap of 2.5 cm	1.4 ms	1 ms max

FIGURE 20 - CONTACT TRAVEL VS. TIME.

Improvements in the contact parting time can be obtained by several methods:

1. Finding the critical adjustment of the latching ball and the operating rod.
2. Increasing the force of the opening spring.
3. Increasing the input energy to the electrodynamic drive.
4. Modifying the differential areas of the contact to obtain a net opening force from the action of the gas.

The opening velocity can be increase by either:

1. Increasing the body diameter of the interrupting contact or
2. Increasing the operating pressure of the interrupter.

Any of the above steps or a combination of them will yield the required performance.

To reduce the mass of the moving part, and provide more design flexibility, a modified ball latch system was conceived and it is shown in Figure 22. The use of opening springs has been eliminated and the initial acceleration is obtained by the pneumatic force that is acting continuously upon the contact.

The latch releasing member has been reduced to a repulsion disc thus minimizing the total mass that is to be moved for the initiation of the trip operation. It has been calculated that the latch can support a load of up to 27000 Newtons (6000 lbs); the expected latch release time is 0.3 ms and the total latch travel has been fixed at 0.76mm. This mechanism is in the conceptual stage and therefore no testing has been done to appraise its performance.

FIGURE 21 - PRESSURE VS. AVERAGE CONTACT VELOCITY

FIGURE 22 - MODIFIED BALL LATCH SYSTEM

PNEUMATICALLY LATCHED MECHANISM

A pneumatically latched mechanism, (Figure 23), is one that utilizes the interrupter high pressure gas for maintaining the contacts close in addition to the now familiar utilization of this pressure as a driving force for opening the contacts.

FIGURE 23 - PNEUMATICALLY LATCHED MECHANISM

By proper dimensioning of differential areas between the sealing surfaces of the interrupting contact it is possible to produce a net force that holds the contact closed. The magnitude of this force is dictated by the gas pressure existing inside the interrupter and the differential area available.

This type of a mechanism is undoubtedly the simplest concept. Only an axial pulling force, developed by an electrodynamic drive, is required to break the gas blast seal thus allowing the pneumatic assist force to drive the contact to the fully open position.

To provide electrical isolation between the moving contact, which is at line potential, and the repulsion disk, located at ground potential, a solid insulating link, or pull rod was used. The length of the rod is dictated by the voltage stress applied along its length, and is therefore dependent on the voltage class of the interrupter.

A series of difficulties are found when such an insulating rod is to be used. Although the application of the rod in itself does not represent a problem, the difficulties arise when metallic ends, to be used as connectors, are attached to the rods.

The complete pull rod assembly must be capable of withstanding the total opening force, which has been calculated at approximately 45000 Newtons (10000 lbs), without showing signs of elongation, or of losing the bond's integrity.

The need for eliminating any possible elongation of the rod is dictated by the close coupling required between the repulsion coil and disk of the electrodynamic drive. Should this coupling increase beyond a 2 to 3mm a noticeable change in the opening time of the interrupter will take place, and in the worst case, when the coupling is lost the interrupter will fail to open.

Since the pull rod assembly represents perhaps the most critical component in this type of operating mechanism, the proposed designs were subjected to a series of tests whose object was to demonstrate the capability of the assembly. In these tests one end of the rod was solidly anchored and an electrodynamic drive was located at the other end. Whenever the impulse coil was energized an impact load was applied to the rod end connectors by the force generated between the impulse coil and the repulsion disc.

The magnitude of the impact load is proportional to the input to the impulse coil which can easily be controlled by changing the values of capacitance or the charge voltage of the power supply.

From measurements done in the past it has been established that the average efficiency of the electrodynamic drive is in the order of 1.5%. It is assumed that the same efficiency value is applicable to the test set-up used

FIGURE 24 - PEAK IMPULSE FORCE VS. INPUT ENERGY TO IMPULSE COIL

in the investigation, and since all the energy is absorbed by the pull rod and stored in the form of strain energy, it is then possible to calculate the relationship between the energy input and the impact load.

The strain energy of the rod can be written as:

$$W = \left(\frac{F^2 \ell}{AE} \right)_{\text{Rod}} + \left(\frac{F^2 \ell}{AE} \right)_{\text{Alumimum connectors}}$$

where

W = Total strain energy (1.5% of the power supply stored energy).

F = average impact force generated by the coil

ℓ = length of test piece

A = cross section area of test piece

E = modulus of elasticity

Because of the larger area A, shorter length ℓ , and higher modulus E of the end connectors, the energy absorbed by the connectors is negligible compared to the energy absorbed by the fiberglass rod, and therefore, the average impulse force is reduced to:

$$F = \left(\frac{WAE}{\ell} \right)^{\frac{1}{2}} \text{ fiber glass rod}$$

and the peak impact force becomes:

$$F_p = 2 \left(\frac{WAE}{\ell} \right)^{\frac{1}{2}}$$

The known parameters are:

$$A = 2.85 \text{ cm}^2 \text{ (0.441 in}^2\text{)}$$

$$E = 4.13 \times 10^6 \frac{\text{Newtons}}{\text{cm}^2} \text{ (6} \times 10^6 \text{ psi)}$$

$$\ell = 21.44 \text{ cm}$$

Substituting these values into the formula for the peak force and substituting the variable effective energy at the impulse coil the following is obtained.

$$F_p = 1.28 \times 10^3 (V) (\sqrt{C})$$

Where

V = charge voltage and

c = capacitance of bank

The calculated values of the peak impulse force are shown graphically in Figure 24.

The tests results obtained when using the rod assembly shown in Figure 25 indicated that an increase in length of up to 8.4mm (0.33 in) can be expected

FIGURE 25 - FIBERGLASS ROD END ASSEMBLY

when the power supply energy is 18000 joules or 76×10^3 Newtons. At the required value of 45×10^3 Newtons an elongation of 2.5mm (.10 in) was observed. The relationship between the elongation and the energy utilized has been plotted and is shown in Figure 26.

FIGURE 26 - PULL ROD ELONGATION VS. OPERATING ENERGY

FIGURE 27 - PULL ROD ELONGATION VS. NUMBER OF OPERATIONS

A second series of tests was performed to determine the cumulative effect on the rod as a function of repeat operation with a constant energy input. Two energy levels were chosen for these tests, 194 Joules (120 μ f at 1800 volts) and 750 Joules (240 μ f at 2500 volts), and a total of 50 operations at each level were performed. The total elongation was measured after each operation.

The results indicate that a set in the total length takes place after a number of operations. This number depends upon the energy level which in turn represents the force applied to the assembly. The results of these tests are shown graphically in Figure 27.

A design modification of the connecting ends was made and is shown in Figure 28. This design incorporates the concept of a holding chuck (item 1) and a collar assembly (item 2) placed at the end of the rod, (item 3), which is held inside the metal connector.

FIGURE 28 - MODIFIED FIBERGLASS ROD END ASSEMBLY

A sample rod was tested under the same conditions of the previous tests. At an energy input of 194 Joules no increase in length was observed, when the input energy was increased to 750 and then to 1037 Joules the observed elongations were 0.05 and 0.1mm respectively.

Based on these results, the pull rod design was judged acceptable and it was adopted for the mechanism used for investigating the performance of an SF₆ interrupter.

2.4 INTERRUPTER INVESTIGATIONS

2.4.1 INTRODUCTION

Undoubtely, the most critical component in the project is the interrupter assembly, and consequently a great deal of effort has been applied in exploring the basic behavior of several interrupter models.

Earlier in the report, when stating the scope of the project, the preliminary objectives for the breaker and the interrupter were tabulated and were shown in Table I. It was also stated that the two interrupting mediums, most likely to succeed, were vacuum and SF₆.

Each of these mediums was investigated independently and the individual performance of both, vacuum and SF₆, was evaluated to determine their potential as synchronous interrupters.

It is general knowledge that the ability of vacuum interrupters, for withstanding high rates of rise of recovery voltage, is superior than that of SF₆. However, SF₆ exhibits its superiority in the ability for withstanding a higher peak of recovery voltage and for interrupting higher magnitudes of current. It is therefore essential that this characteristic behavior of each interrupting medium be taken into account for an overall evaluation of interrupting performance.

2.4.2 VACUUM INTERRUPTER

A great deal of literature is available describing the physics of the arc interruption in vacuum, and some of the applications of vacuum interrupters. A list of references (7 to 31 inclusive) is given in this report,

however, this list should not be construed to be a complete bibliography in the subject but only a collection of material reviewed during our vacuum investigations.

It is known that in the past the possibility of utilizing vacuum interrupters for synchronous current interruption has been investigated; However, no published material has been found in the subject. The same lack of published data exist for recovery voltages of vacuum interrupters operated at controlled arcing times of approximately 1 ms. Some of the published data for longer arcing times has been tabulated and is included in Table III.

Most of the existing literature on the interrupting behavior of vacuum deals with arcing times much longer than those contemplated in this application. Moreover, the data deals with currents considerably smaller than the 100kA RMS that is being sought as the interrupting rating for this development program.

The possibility of developing a vacuum interrupter, specifically designed for synchronous operation was considered. But it was argued that in view of the large number of variables that directly influence the interrupting performance, and the time constraints for completion of the project it would be preferable to explore the possibility of using a standard, readily available interrupter. It was generally agreed that if evidence could be found of a dramatic increase in performance brought about by reducing the arcing time to the order of 1 ms or less; then vacuum interrupters can be considered as offering a definite probability of success for synchronous application.

There are a number of models of vacuum interrupters, from different manufacturers, from which a selection could be made. Knowing that the peak voltage recovery capability is one of the handicaps of vacuum interrupters it was decided to select an interrupter that had reportedly been tested at voltage levels corresponding to the transmission class. (Reference 32, 33). The interrupter reportedly used in those tests was one that uses a CLR contact material, (Appendix I), which incidentally is a type of contact material that has exhibited characteristics that are superior to those of copper alloy contacts. The interrupter is manufactured by Westinghouse and is identified as Model No. WL-23340. A complete set of specifications for this interrupter is enclosed as Table IV.

TABLE III

Recovery Strength of Vacuum Interrupters

Description of Contact	Interrupting Current	Recovery Strength		Source
Silver contacts diameter (d): 1.27 cm 5.08 cm contact gap (g): 0.76mm 2.3 mm 4.6 mm	forced extinction (in 0.5 μ s) of a 250 A arc after 3 ms arcing	diameter and gap	$RRRV_i^*$, kV/ μ s	Rich & Farrall (Ref. 26)
		d = 1.27 cm:		
		g = 0.76mm	9	
		g = 2.3 mm	8	
		g = 4.6 mm	9	
		d = 5.08 cm:		
		g = 0.76mm	8	
		g = 2.3 mm	7	
		g = 4.6 mm	5	
Material varied d : 3/4"	1/2 cycle 60Hz arc- ing with 400 - 3200 A peak current	material and peak current	$RRRV_a^{**}$, kV/ μ s	Cobine & Farrall (Ref. 29)
		Be :		
		400 A	~ 6	
		3200 A	~ 0	
		Zn : 400 A	~ 1.5	
		1600 A	~ 1.5	
		Cu ₃ Sn :		
		400 A	~ 5	
		1600 A	~ 4	
		Cu-W-Th :		
		400 A	~ 8	
		1600 A	~ 3	
		Ag :		
		400 A	~ 6	
		1600 A	~ 5	
		3200 A	~ 4	
		Cu-Bi :		
		400 A	~ 5	
		1600 A	~ 5	

TABLE III (Continued)

Recovery Strength of Vacuum Interrupters

Description of Contact	Interrupting Current	Recovery Strength		Source
copper contacts d : 2 5/8" g : 1/2" spiral slots	rated 27kA rms at 18kV.		RRRV _i [*] , kV/μs	Lee et al. (Ref. 28)
			6	
butt copper contacts d : 2.5 cm g : 0.6 cm 1.3 cm	forced interruption of 930 A d.c. arc after 8 ms arcing	g = 0.6 & 1.3 cm	RRRV _a ^{**} , kV/μs	Kimblin (Ref. 12)
			2 - 3	
copper contacts d : 2 5/8" g : 3/4" spiral slots	45kV - 40kA model: di/dt ≥ 20 A/μs	Model	RRRV _i [*] , kV/μs	Kurtz et al. (Ref. 11)
	45kV - 50kA model: di/dt = 26 - 28 A/μs	45kV - 40kA 45kV - 50kA	3.3 - 6.0 4.0 - 5.0	

* RRRV_i : initial rate of rise of recovery voltage

** RRRV_a : average rate of rise of recovery voltage
for a period of 10 μs after current zero.

MECHANICAL CONSIDERATIONS

Traditionally most vacuum interrupters have been operated at opening speeds ranging from, 1.2 to 3 m/sec, (4 to 10 ft/sec.) These relatively low opening speeds have proven to be adequate for the common applications of these interrupters; However, if the scope of their application is to be extended to the transmission voltage class, and moreover, if their applicability to the concept of synchronous interruption is to be considered, the opening speeds of these interrupters must be increased to a range of 6 to 12 m/sec, (20 - 40 ft/sec). Such an increase in the opening velocity is undoubtedly going to impose a heavy burden in the mechanical integrity of the interrupter as a whole but more particularly upon the bellows.

Normally the mechanical life of a vacuum interrupter has been proven to be well in excess of 10000 operations. As the initial step in our investigations, it was decided to demonstrate that the selected interrupter was capable of at least 100 operations without signs of mechanical damage. In the future and if the interrupter proves to be suitable for this kind of application additional mechanical tests to determine the limit of endurance will be performed. The present 100 operations requirement is only to assure that all testing can be performed without developing mechanical problems in the vacuum bottle.

Using the pneumatically assisted operating mechanism, described earlier in this report and shown in Figure 14, a vacuum interrupter was operated a total of 100 times at a contact opening velocity of 6 m/sec (20 ft/sec).

The criteria used for judging the integrity of the interrupter during the course of the test was the ability of the interrupter to withstand a Hi-Pot test at a level of 38kV RMS. This test was performed in accordance with the instructions of the interrupter's manufacturer.

Subsequent to the mechanical testing the interrupter was cut open and inspected for any signs of deformation of the contacts, or deterioration and damage of the bellows, no evidence of damage was found and therefore this design of a vacuum interrupter was judged as being suitable for continuing testing.

TABLE IV

VACUUM INTERRUPTER

WESTINGHOUSE TYPE: WL-23340

ELECTRICAL RATINGS, 3 Phase Rating Symmetrical

Basis Rated Frequency.....	60		Hertz
Rated Maximum Line-to-Line Voltage.....	15.5	rms	kilovolts
Rated Voltage Range Factor K.....	1.0		
Rated Low Frequency Withstand Voltage.....	50	rms	kilovolts
Rated Full Wave Impulse Withstand Voltage.....	110	crest	kilovolts
Rated Continuous Current.....	600	rms	amperes
Generated Heat Loss:			
@ 600 amps 125 pounds contact force	20		watts
Rated Short Circuit Current (Symmetrical).....	12,000	rms	amperes
Asymmetry Ratio S, Maximum.....	1.2		
Momentary, Close-and-Latch (Asymmetrical):			
@ 125 pounds contact force.....	20,000	rms	amperes
3-Sec. Short-Time Carrying Capability.....	12,000	rms	amperes
Rated Capacitor Switching Current, Max.....	600	rms	amperes

MECHANICAL DATA

Interrupter Weight.....	6.5		pounds
Moving Part Weight.....	1.3		pounds
Contact Force from Atmospheric Pressure.....	20		pounds

MECHANICAL REQUIREMENTS

Contact Stroke.....	0.38		inch
Opening Speed, Average to 0.28 inch Gap.....	3.5-4.0		feet-per-second
Overtravel During Opening. Max.....	0.12		inch
Closing Speed. Average of Last 0.13 inch.....	2.5-3.0		feet-per-second
Contact Bounce Duration, Max.....	0.002		second
Added Force for Momentary:			
20,000 amps rms (asymmetrical).....	125		pounds

LIFE

Mechanical Life:

@ 0.38 inch contact stroke.....	10,000		operations
Contact Erosion Limit.....	0.12		inch

DIELECTRIC PERFORMANCE

The two interrupters, intended for our investigations, were subjected to dielectric withstand tests directed to verifying the integrity of the interrupters as they were received from the factory, and to pre-condition the interrupter prior to power testing.

The tests were conducted following the standard testing procedures specified by the American National Standard, C37.078 - 1972 (IEEE std 343 - 1972). The interrupters were subjected to a 50kV 60Hz withstand and to a $1.2 \times 50 \mu s$ impulse wave at a voltage level of 110kV. Both interrupters were able to successfully withstand three successive impulse tests of positive and negative polarities as well as the low frequency test.

1-COS VOLTAGE RECOVERY

Vacuum interrupters are generally known for having a good capability for recovering to high rates of rise of voltage. They are sensitive however to the peak value of the recovery voltage and are unable to successfully withstand high amplitudes of voltage. It is therefore quite indispensable to evaluate the characteristic voltage recovery capability of the proposed interrupter.

For the intended application, in the event of a short line fault the rate of rise of recovery voltage is very high ($22kV/\mu s$). The peak voltage however is only 43kV and if divided between multiple interrupters in series is not far beyond the voltage rating of the interrupter being used, but when a terminal fault takes place the peak voltage is 338kV as it has been shown in Table I. It must be recognized that the above value applies when two breaks are used for a 345kV breaker; however, as it has been stated previously, it is intended to use at least four vacuum interrupters in series and therefore the required voltage reduces to 182kV (assuming a 54% voltage distribution) across each interrupter.

The ultimate recovery capability of an interrupter is that which is obtained in the absence of any arcing, and is rather obvious that this capability will be degraded in the presence of an electric arc.

This ultimate recovery capability was investigated by means of a simulated switching surge. This test voltage had a typical (1-cos) wave form at a frequency of 240kHz and a variable total voltage crest.

Initially the vacuum interrupter was located standing in free air and the voltage was applied across the open contact. An external flashover at a voltage level of 54kV was observed between the high voltage terminal and the interrupter's shield. The current flow caused by the flashover was estimated at 2kA. To ascertain that no damage of the interrupter, due to the flashover to the shield, had taken place and furthermore to determine the external flashover level the following values of an impulse voltage were applied across the interrupter:

Positive polarity:

Random flashover	132-135kV*
3 successive full waves	135kV
3 successive flashovers	138kV*

Negative polarity:

Random flashover	121kV*
2 successive full waves	123kV
Continuous flashover	125kV*

*In all cases the flashovers were external to the interrupter.

To eliminate the external flashover problem the interrupter was placed inside of a plexiglass container filled with SF₆ at a pressure of 30 psig.

The simulated switching surge tests were then resumed and the interrupter successfully withstood crest voltages of up to 151kV. An internal flashover and therefore a failure of the interrupter took place at 160kV. Enclosed are Figures 29 and 30 showing a success and a failure respectively.

The test results clearly indicated that it is not possible to obtain the capability from the interrupter to recover to 181kV. Since only 160kV represents its ultimate capability under no arcing conditions.

FIGURE 29 - SUCCESSFUL SIMULATED SWITCHING SURGE TEST ON VACUUM BOTTLE

FIGURE 30 - INTERNAL FAILURE OF VACUUM BOTTLE FOR SIMULATED SWITCHING SURGE TEST

Later investigations performed, independently of this project, on a vacuum interrupter of a similar design but having a higher interrupting rating (Reference 34) served to establish a maximum voltage breakdown of 86.5kV after interruption of 20kA with an approximate arcing time of 4 ms.

Based on these results it can be concluded that a minimum of four (4) interrupters in series would be required for a 145kV rating and at least eight (8) interrupters for a 345kV breaker. Nevertheless, it must be remembered that the above requirements are dictated by the limitation imposed by the voltage rating of the available interrupter (15kV). It is probable that the required number of interrupters can be reduced if vacuum interrupters having a higher voltage rating are utilized; However, these interrupters are only recently being developed, and therefore, their availability is limited.

A re-evaluation of these findings may be appropriate when further advances in the state of the art of vacuum interrupters takes place.

CONTACT WELDING AND BLOWOUT FORCES

Contact welding is practically unavoidable in a vacuum interrupter because of the cleanliness of the metallic surfaces. The forms of contact welding and their causes can be classified as:

- Cold welding - due to high pressure
- Diffusion welding - due to elevated temperatures
- Resistance welding - due to high current
- Percussion welding - due to arcing prior to contact closing

The amounts of cold welding and of diffusion welding are not expected to be substantial. Percussion welding can be discounted because of the operating philosophy of the synchronous breaker design where the vacuum interrupter is relieved of any current making duty. Therefore the only mode of welding that can have a significant influence on the interrupter is Resistance welding. This type of contact welding is likely to occur due to the momentary current (100kA rms) and the short time current (225kA peak).

References 35 to 39 inclusive, can be used to review some of the theory explaining the phenomena of resistance welding on contacts.

It is known that for flat contacts only a few junction points will conduct current, and that the voltage across the contact is related to the maximum temperature which is attained at the narrowest point of contact. For copper contacts, for example, the melting temperature of 1083°C corresponds to a contact constriction voltage of 430 mV.

The temperature of the constricting areas of the contact normally follow the values of current very closely on a time scale of milliseconds. The peak currents therefore become the controlling factor for resistance weld forces.

The initial weld current which produces incipient melting depends on the contact material, the radius of curvature of the mating surfaces and the contact pressure. Some typical values for contacts in air with a 15mm radius of curvature and 10kg contact force are listed below:

MATERIAL	PEAK CURRENT FOR INCIPIENT MELTING (WELDING) [KA]	WELDFORCE [kg/mm ²]
Au	About 12 extrapolated	
Ag	5.8	16
Cu	4.3	33
Al	About 2.2 extrapolated	
Cu - Be	About 0.65 extrapolated	
Mo	2.3	19
Ag-Ni 99.9/0.1	5.2	30
Ag-Cu 80/20	4.5	33
Ag-Graphite-Ni 96.5/3/0.5	5.7	1

Figure 31, reproduced from Reference 39, the maximum weld forces can be estimated. Extrapolation of the curves indicate that maximum weld forces between 4.5 to 9 kilonewtons (1000 to 2000 lbs) can be expected with peak currents of 225kA across flat contacts that are held closed with a force of 1.6 kilonewtons (350 lbs).

This magnitude of forces is too high, specially where several interrupters are to be connected in series. Therefore, it should be recognized that a potential problem exists. Possible methods of solution are: An increase in the holding force; the use of an impulse force to initiate the contact's

FIGURE 31 - RESISTANCE WELD STRENGTHS VS. CURRENT
FOR CLR CONTACTS AND A HOLDING FORCE
OF 350 LBS

opening; or the use of an opening mechanism that produces a net bending moment at the contacts. These, or any other mechanical methods, for overcoming the welding forces are restricted by the time limitations inherent to the high operating speeds needed for synchronous interruption.

Another alternative for the solution of the welding problem is the use of multiple parallel contacts; However, this approach defeats the basic desire of using a standard interrupter and will entail the development of a completely new concept of vacuum interrupter.

The blow-out, or contact opening forces also appear to present a difficult problem and can be considered as another obstacle to the use of vacuum interrupters.

The electrodynamic lift-off force exerted by the current between flat contact surfaces is given by the following empirical equation:

$$F_a = 0.051(I)^2 \text{ (Reference 36)}$$

where

F_a is the blow-out force in kilograms force

I is the peak current in kA that passes through the contacts.

Using the above equation the lift-off force corresponding to a peak current of 225kA is calculated as 25.5 kilonewtons (5700 lbs).

Again a possible solution to this problem is a complete redesign of a vacuum interrupter to accommodate a contact such that net compressive forces are generated by the short circuit current. This design requirement presents a very difficult problem for a vacuum interrupter, while the design concept is standard for interrupters operated in mediums other than vacuum.

CURRENT INTERRUPTION

Data relating to the short line fault transient recovery voltage capability was needed to complete the evaluation of the vacuum interrupter. To gather the needed information two series of current interrupting tests were performed. The first series of tests was carried out utilizing a high frequency capacitive discharge while in the second series standard synthetic test procedures were used.

CAPACITIVE DISCHARGE TESTS

This method of testing has been generally referred as the "Direct Synthetic test method". It basically consists of a Weil's synthetic test set-up where the low frequency source, (generator current), has been omitted and only

the high frequency discharge portion of the set-up is utilized. The shape of the recovery voltage is easily controlled by means of a simulated transmission line.

It is a general practice to use at least 5 "Pi" sections to simulate the transmission line, in our case and for the purpose of expediency, only two sections were used.

The triangular wave, characteristic of the short line fault recovery voltage, can be represented by the series:

$$f(t) = \frac{8}{\pi^2} \left(\cos 2\pi t + \frac{1}{9} \cos 3 \times 2\pi t + \frac{1}{25} \cos 5 \times 2\pi t + \dots + \frac{1}{n^2} \cos n2\pi t + \dots \right)$$

It can be shown that the use of two sections will produce the fundamental frequency and a third harmonic. The sum of these two terms yields a wave form with an amplitude of 0.903 times the maximum amplitude of the triangular wave. The addition of the third harmonic modifies the slope of the fundamental term and as is easily demonstrated the maximum slope of 5.1 per unit of the sinusoid is reduced to match the 4 per unit slope of the triangular wave; Thus, closely simulating the initial ramp of voltage characteristic of a short line fault TRV the only discrepancy is the peak amplitude of the voltage.

A schematic diagram of the test set-up and the instrumentation used during these tests is shown in Figure 32.

The direct synthetic test method is characterized by a high frequency pulse of current that has a relatively low current peak, and therefore, it limits the total energy input to the interrupter as well as the instantaneous value of current at contact part. These are severe limitations since in a vacuum interrupter the curve of the recovery strength is determined by the rate of vapor dispersion which in turn is a function of current. Nevertheless, it is expected that valuable information can be gained using this test method and supplemented later by results obtained using the full synthetic test method.

FIGURE 33 - 1. RATED INTERRUPTER CURRENT OF BOTTLE TESTED (60Hz)
 2. PULSED CURRENT DIRECT SYNTHETIC
 3. (60Hz) di/dt EQUIVALENT TO DIRECT SYNTHETIC di/dt

The interrupter operating parameters were constant as follows:

Average contact velocity	5.2 to 6 m/sec
Contact gap (at interruption)	6.4 mm
Arcing time	1.2 ms
Time to contact part	0.2 ms
Impulse coil power supply	240 μ f; 1900 volts
Mechanism pressure	2756 kilopascals

Oscillographic records were obtained at two sweep speeds. At the low speed sweep (0.5 ms/cm) a recording was made of the test current. At the higher sweep speed (5 μ s/cm) records were taken of the di/dt and the dv/dt at the instant of current zero. A typical set of these records are included in Figures 34 and 35. And a complete tabulation of the tests results is shown in Table V.

TABULATION OF DATA - TABLE NO. V

VACUUM INTERRUPTER WL-23340

DIRECT SYNTHETIC TESTS

No.	PASS or FAIL	di/dt A/μs	de/dt CAL. kV/μs	ARC TIME ms	$\hat{I}$ kA	de/dt kV/μs	E _O kV	C _{L/2} μf	L _{L/2} μh	L _S μh	C _B μf
8	FAIL	20	9.0	0.8	10.2	9.7	20	.001	203	400	280
9	FAIL	20	9.0	1.0	10.2	9.7	20	.001	203	400	280
10	PASS	20	9.0	1.2	10.2	9.7	20	.001	203	400	280
11	FAIL	20	12.7	1.2	10.2	11.7	20	.0005	203	400	280
14	FAIL	30	9.7	1.2	15.9	-	26	.001	105	500	370
15	FAIL	30	7.9	1.2	15.9	-	26	.0015	105	500	370
16	FAIL	30	6.9	1.2	15.9	-	26	.002	105	500	370
17	FAIL	30	5.6	1.2	15.9	5.7	26	.003	105	500	370
18	FAIL	30	4.8	1.2	15.9	4.8	26	.004	105	500	370
19	FAIL	30	21.8	1.2	15.9	14.5	26	.0002	105	500	370
21	FAIL	30	4.8	1.4	15.9	4.8	26	.004	105	500	370
22	FAIL	30	4.8	1.2	15.9	4.8	26	.004	105	500	370
23	PASS	30	4.8	1.2	15.9	4.8	26	.004	105	500	370
24	FAIL	30	3.4	1.2	15.5	4.8	26	.008	105	500	370
25	FAIL	30	3.4	1.2	15.5	4.8	26	.008	105	500	370
26	PASS	30	3.4	1.2	15.5	4.8	26	.008	105	500	370
27	FAIL	30	3.4	1.2	15.5	4.8	26	.008	105	500	370
28	PASS	30	3.4	1.2	15.5	4.8	26	.008	105	500	370
29	FAIL	30	4.9	1.2	15.5	5.7	26	.004	105	500	370
32	PASS	20	9.0	1.2	10.6	9.7	20	.001	203	400	280
34	PASS	20	9.0	1.2	10.6	9.7	20	.001	203	400	280
35	PASS	20	12.7	1.2	10.6	14.6	20	.0005	203	400	280
36	PASS	20	12.7	1.2	10.6	14.6	20	.0005	203	400	280
37	PASS	20	12.7	1.2	10.6	14.6	20	.0005	203	400	280
40	PASS	25	11.3	1.2	12.6	12.4	24.5	.001	203	400	280
42	PASS	25	15.9	1.2	12.6	14.6	24.5	.0005	203	400	280
43	FAIL	25	15.9	1.2	12.6	17.1	24.5	.0005	203	400	280
46	PASS	30	6.9	1.2	14.3	9.7	26	.002	105	500	280

TABULATION OF DATA - TABLE NO. V (Continued)

VACUUM INTERRUPTER WL-23340

DIRECT SYNTHETIC TESTS

No.	PASS or FAIL	di/dt A/μs	de/dt CAL. kV/μs	ARC TIME ms	$\hat{I}$ kA	de/dt kV/μs	E _o kV	C _{L/2} μf	L _{L/2} μh	L _s μh	C _B μf
47	PASS	30	6.9	1.2	14.3	9.7	26	.002	105	500	280
48	PASS	30	9.7	1.2	14.3	11.6	26	.001	105	500	280
50	PASS	30	9.7	1.2	16.3	11.6	26	.001	105	500	370
51	PASS	30	9.7	1.2	16.3	11.6	26	.001	105	500	370
53	PASS	35	11.3	1.25	16.3	12.9	21	.001	105	270	370
54	FAIL	35	11.3	1.25	15.9	12.9	21	.001	105	270	370
55	FAIL	35	11.3	1.35	15.5	12.9	21	.001	105	270	370
56	FAIL	35	11.3	1.35	15.5	12.9	21	.001	105	270	370
57	FAIL	35	8.0	1.35	15.5	9.7	21	.002	105	270	370
60	FAIL	30	6.9	1.2	16.3	8.3	26	.002	105	500	370
61	PASS	30	6.9	1.3	16.3	8.3	26	.002	105	500	370
62	FAIL	30	6.9	1.3	16.3	8.3	26	.002	105	500	370
64	FAIL	35	4.6	1.3	17.1	6.1	21	.006	105	270	460
65	PASS	35	4.0	1.4	17.1	5.3	21	.008	105	270	460
66	PASS	35	4.0	1.35	17.1	5.3	21	.008	105	270	460
68	PASS	35	4.0	1.35	17.5	5.8	21	.008	105	270	460
69	FAIL	35	4.6	1.3	17.1	6.5	21	.006	105	270	460
72	FAIL	39	4.6	1.3	20	6.1	24.5	.008	105	270	460
74	FAIL	41.5	2.0	1.35	19.2	-	21.5	.008	20	270	460
75	FAIL	40	2.0	1.35	18.8	-	21	.008	20	270	460
78	PASS	26	8.1	1.35	12.2	10.5	21.5	.001	110	500	280
79	FAIL	25	8.1	1.15	11.4	10.5	21.5	.001	110	500	280
80	PASS	25	8.1	1.3	12.2	10.5	21.5	.001	110	500	280
81	PASS	25	11.5	1.3	11.8	14.5	21.5	.0005	110	500	280
82	PASS	25	11.5	1.3	11.8	14.5	21.5	.0005	110	500	280
83	PASS	25	11.5	1.33	11.8	14.5	21.5	.0005	110	500	280
90	PASS	24.6	11.5	1.3	18.7	10.8	27	.0005	110	730	560

FIGURE 34 - INTERRUPTING TEST VACUUM INTERRUPTER

TIME = 500 μ s/DIV
 I = 8160 A/DIV
 E(ARC) = 50 V/DIV

FIGURE 35 - INTERRUPTING TEST VACUUM INTERRUPTER

TIME = 5 μ s/DIV
 I = 102 A/DIV
 E(TRV) = 9725 V/DIV

These same results have been plotted and an estimated curve showing the relationship between di/dt and dv/dt is given in Figure 36. From this figure, as it was expected, the typical decrease in dv/dt capability with an increase of di/dt can be observed.

It is clearly demonstrated that even under these tests conditions, which are advantageous to the interrupter, values of recovery voltage at a di/dt of 48 A/ μ s will not be sufficient for the application in mind. If 4 interrupters in series are used then each will have to withstand a dv/dt of approximately 6.6kV/ μ s. This level is achieved with only 34 A/ μ s on the tested interrupter.

To investigate the possibility of increasing the recovery voltage by using an interrupter having a higher interrupting rating, a new interrupter, Westinghouse Model WL-23342A was tested under the same conditions used for the previous interrupter. The complete list of specifications for the new interrupter is given in Table VI.

The tabulation of the test results obtained with this interrupter is included in Table VII and the graphical interpretation of these results is shown in Figure 36. As it can be seen from this figure the estimated performance curve for the 18kA interrupter shows that it coincides, exceptionally well, with the curve for the 12kA interrupter.

This similar performance of the interrupters suggest that: The short line fault TRV capability of a vacuum interrupter is independent of the current interrupting rating of the unit provided that the interrupter is operated under controlled arcing time conditions and the energy input to the arc does not exceed a certain limit. This limit is defined by the curve shown in Figure 37, where the integral of the current over time ($\int i dt$) have been calculated from the experimental results and have been plotted against the limits of dv/dt . The results suggest that the dv/dt capability is proportional to the total ampere seconds of the arc raised to some power which can be approximated to a value of -3.3.

$$dv/dt \propto (\int i dt)^{-3.3}$$

TABLE VI

VACUUM INTERRUPTER

WESTINGHOUSE TYPE: WL-23342

ELECTRICAL RATINGS, 3 Phase Rating Symmetrical

Basis Rated Frequency.....	60		Hertz
Rated Maximum Line-to-Line Voltage.....	15.5	rms	kilovolts
Rated Voltage Range Factor K.....	1.3		
Rated Low Frequency Withstand Voltage.....	50	rms	kilovolts
Rated Full Wave Impulse Withstand Voltage.....	110	crest	kilovolts
Rated Continuous Current.....	1200	rms	amperes
Generated Heat Loss:			
@ 1200 amps 500 pounds contact force	30		watts
@ 2000 amps 500 pounds contact force	80		watts
Rated Short Circuit Current (Symmetrical).....	18,000	rms	amperes
Asymmetry Ratio S, Maximum.....	1.2		
Momentary, Close-and-Latch (Asymmetrical):			
@ 500 pounds contact force.....	40,000	rms	amperes
@ 950 pounds contact force.....	60,000	rms	amperes
3-Sec. Short-Time Carrying Capability.....	23,000	rms	amperes
Rated Capacitor Switching Current, Max.....	600		

MECHANICAL DATA

Interrupter Weight.....	12.5		pounds
Moving Part Weight.....	2.5		pounds
Contact Force from Atmospheric Pressure.....	37		pounds

MECHANICAL REQUIREMENTS

Contact Stroke.....	0.5		inch
Opening Speed, Average to 0.38 inch Gap.....	4.0-5.0	feet-per-second	
Overtravel During Opening, Max.....	0.25		inch
Closing Speed, Average of Last 0.17 inch.....	2.5-3.5	feet-per-second	
Contact Bounce Duration, Max.....	0.0002		second
Added Force for Momentary:			

40,000 amps rms (asymmetrical).....	500		pounds
60,000 amps rms (asymmetrical).....	950		pounds

LIFE

Mechanical Life:

@ 0.5 inch contact stroke.....	10,000		operations
Contact Erosion Limit.....	0.12		inch

FIGURE 36 - VACUUM INTERRUPTER DIRECT SYNTHETIC
TESTS RECOVERY VOLTAGE CAPABILITY

TABULATION OF DATA - TABLE NO. VII
WESTINGHOUSE VACUUM BOTTLE (WL-23342A)
DIRECT SYNTHETIC TESTS

TEST NO.	PASS OR FAIL	di/dt kA/ μ s	de/dt kV/ μ s	ARC TIME ms	$\hat{I}$ kA
5	FAIL	20.7	6.8	1.2	9.0
6	FAIL	20.1	6.8	1.2	9.0
7	PASS	16.0	5.8	1.2	7.3
8	PASS	20.1	6.8	1.2	9.0
9	PASS	20	8.1	1.2	9.8
10	PASS	20	10.6	1.2	9.0
11	FAIL	25.5	8.0	1.2	11.4
12	PASS	20	6.8	1.2	9.8
13	PASS	24.5	6.14	1.2	10.6
14	PASS	24.5	7.8	1.2	11.4
15	PASS	24.3	11.7	1.2	11.4
16	FAIL	25.5	13.0	1.2	11.4
18	FAIL	25.5	11.7	1.2	11.4
20	PASS	24	7.3	1.2	11.4
21	FAIL	25.0	11.7 cal	1.2	11.4
22	FAIL	25	8 cal	1.2	11.4
23	PASS	25	8 cal	1.2	11.4
27	FAIL	30	5.1	1.2	13.6
29	PASS	30	4.4	1.2	13.6
31	FAIL	30	5.1	1.2	13.6
32	FAIL	30	4.7	1.3	13.6
33	FAIL	30	4.4	1.3	13.6
34	FAIL	30	4.4	1.1	13.6
35	FAIL	30	4.4	1.2	13.6
36	PASS	30	4.4	1.2	13.6
37	FAIL	30	4.4	1.2	13.6
40	PASS	25	3.7	1.2	11.4
41	FAIL	25	3.7	1.2	11.4
46	PASS	29.2	4.3	1.2	13.6

TABULATION OF DATA - TABLE NO. VII (Continued)

WESTINGHOUSE VACUUM BOTTLE (WL-23342A)

DIRECT SYNTHETIC TESTS

TEST NO.	PASS OR FAIL	di/dt kA/ μ s	de/dt kV/ μ s	ARC TIME ms	$\hat{I}$ kA
47	PASS	28.5	5.5	1.2	13.6
48	FAIL	28.5	7.0	1.35	13.6
49	PASS	29	6.5	1.15	13.6
50	FAIL	29	6.5	1.4	13.6
52	PASS	29.0	7.3	1.45	13.9
53	PASS	29.0	7.3	1.5	13.9
54	PASS	28.5	8.0	1.4	13.9
55	PASS	28.5	7.9	1.3	13.9
56	FAIL	28.5	-	1.3	13.9
56-1	FAIL	28	8.7	1.35	13.9
57	PASS	30.6	6.48	1.3	13.9
58	PASS	25	8.3	1.25	11.4
59	PASS	25	10.6	1.3	11.4
61	PASS	25	12.3	1.3	11.4
64	PASS	25.5	12.3	1.3	12.2
65	PASS	26	13.0	1.3	12.6
71	PASS	33.0	5.8	1.35	15.0
72	FAIL	35.5	6.9	1.4	16.7
73	FAIL	34	5.2	1.4	16.7
74	FAIL	33.5	6.9	1.35	16.7
75	FAIL	32	5.6	1.4	15.9
78	PASS	33.5	4.9	1.4	15.9
81	PASS	33.5	4.9	1.15	15.9
82	PASS	33.5	4.9	1.35	15.5
83	PASS	33.0	5.2	1.35	15.5
84	PASS	33.0	7.3	1.2	15.5
89	FAIL	30.0	-	1.47	17.2
90	PASS	30.0	5.8	1.5	17.2

FIGURE 37 - INTEGRAL OF CURRENT VS. RATE OF RECOVERY VOLTAGE

A rather interesting performance degradation of the vacuum interrupter was observed during these tests. Whenever a bad failure to interrupt had taken place successful interruption previously achieved at a moderate rate can not be repeated initially; However, after a reconditioning process, consisting of interruptions at very low levels of di/dt and dv/dt , the previous limit of interrupting levels of the vacuum bottle can be regained. This peculiar behavior of the interrupter represents an obviously undesirable characteristic that reduces the confidence level of the interrupter.

The erosion pattern of the contacts was examined, and based on the observations it can be assumed that the arc was in a diffused mode. This arc condition then justifies the capability of the interrupters tested for high TRV rates. It also seem apparent from the burning pattern of the contacts that the arc motion might have been somewhat reduced in the larger contacts. Photographs of the contacts are shown in Figures 38 and 39.

FULL SYNTHETIC TESTS

After completion of the direct synthetic investigations a series of exploratory tests to determine the capability of a vacuum interrupter were performed using the full synthetic testing facility. The object of these tests was to verify the dependence in the performance of a vacuum interrupter upon the arc's energy input.

The tests were conducted at di/dt values of 15, 20 and 25 Amp/ μ s which corresponds to currents of 28, 37, 47kA RMS respectively.

At a di/dt of 15 Amp/ μ s successful interruptions were observed with a dv/dt varying from 2.4 to 9.6kV/ μ s. However, at a later test, and after several failures at higher levels of di/dt , the interrupter failed to clear a di/dt of 15 A/ μ s and a dv/dt of 6.8kV/ μ s, which had cleared previously. This behavior appears to support the findings, when using a direct synthetic test method, that showed a performance degradation and a need for reconditioning of the interrupter.

FIGURE 38 - CONTACTS FROM WESTINGHOUSE VACUUM INTERRUPTER
TYPE WL-23340

FIGURE 39 - CONTACT FROM WESTINGHOUSE VACUUM INTERRUPTER
TYPE WL-23342

When the di/dt was raised to 20 A/ μ s only in one occasion the interrupter cleared successfully at a surprising value of dv/dt (12kV/ μ s). However, in later tests the interrupter failed at every level of dv/dt from a minimum value of approximately 3kV/ μ s. At a di/dt of 25 A/ μ s no successful interruptions were observed.

The tabulation of the tests results is included as Table VIII, and a typical oscillogram record is shown in Figure 40.

From the small number of test results available it is possible to observe that the relationship between the ampere-seconds of arcing and the TRV capability of the interrupter, as determined from the direct synthetic test results, does hold. The total kA-sec required for the application of the vacuum interrupter to a 100kA synchronous breaker is .026kA-sec. At this energy level the required dv/dt for each interrupter is approximately 8kV/ μ s. It has been demonstrated that this TRV capability is achieved when only .015kA-sec are seen by the interrupter. If the results are extrapolated, to estimate the recovery capability at .026kA-sec it is seen that only an approximate dv/dt of 1500 V/ μ s can be expected.

2.4.3 SULFUR HEXAFLUORIDE (SF_6) INTERRUPTER

The use of SF_6 as the interrupting media for conventional power circuit breakers, especially those in the high voltage class (115kV and above), has gained widespread acceptance among the industry during the past two decades.

A great deal of research has been done to study the characteristic behavior of an SF_6 circuit breaker, and therefore, a good understanding of the capabilities and limitations of SF_6 circuit breakers is available.

SF_6 has demonstrated to be an outstanding insulating media, and arc quenching agent. However, it has been observed, and is generally accepted, that the inherent recovery of SF_6 makes an interrupter highly susceptible to high rates of rise of recovery voltage that occur during the first few microseconds after current interruption. Once this critical period of time has elapsed the capability of the interrupter to withstand the ex-cos envelope of the transient recovery voltage, characteristic of a terminal fault, becomes

FIGURE 40 - TYPICAL OSCILLOGRAM RECORD OF FULL SYNTHETIC TEST PERFORMED ON VACUUM INTERRUPTER

TABULATION OF DATA - TABLE NO. VIII

SYNCHRONOUS VACUUM BREAKER

FULL SYNTHETIC TESTS

TEST NO.	PASS OR FAIL	di/dt A/μs	de/dt CAL. kV/μs	ARC TIME ms	i _{part} kA	I _{rms} kA	de/dt kV/μs	E _o kV	C _{L/2} μf	L _{L/2} μh
16	PASS	14.8	6.8	1.5	10.3	26	4.9	14.5	.001	203
17	PASS	20	12.7	1.4	18	38	-	19.5	.0005	203
18	FAIL	24.5	11.3	1.4	20	46	-	24.5	.001	203
19	FAIL	25	8.0	1.2	22	46	-	24.5	.002	203
20	FAIL	25	4.0	-	-	46	-	24.5	.008	203
21	FAIL	25	4.0	1.2	22	46	-	24.5	.008	203
22	FAIL	20	3.2	1.6	18	38	-	19.5	.008	203
23	PASS	15	2.4	1.1	12	28	-	14.5	.008	203
24	FAIL	20	3.2	1.2	18	38	-	19.5	.008	203
25	FAIL	15	2.4	1.0	12	28	2.1	14.5	.008	203
26	PASS	15	2.4	1.4	15	28	-	14.5	.008	203
27	FAIL	15	6.8	1.3	14	28	5.3	14.5	.001	203
29	PASS	15	6.8	-	-	28	5.3	14.5	.001	203
30	PASS	15	9.6	-	-	28	7.3	14.5	.0005	203
33	FAIL	20	9.0	-	-	38	-	19.5	.001	203
34	FAIL	20	3.2	1.4	20	38	2.9	19.5	.008	203
35	FAIL	20	3.2	2.0	37	38	-	19.5	.008	203
36	FAIL	15	6.8	-	-	28	-	14.5	.001	203

more dependent upon the design geometry rather than the gas characteristics. It follows then that a suitable design exhibiting a good dielectric capability and properly designed gas flow patterns can be expected to perform satisfactorily during interruption of terminal faults. However, its performance will be limited to what it can do during a short line fault (kilometric fault). (Reference 40 to 46 inclusive)

Judging then that the most critical condition corresponds to a short line fault most of the effort was devoted to establishing limits of performance of model interrupters for several values of di/dt at corresponding levels of dv/dt .

INTERRUPTER DESIGN

In at least one instance, Reference 2, 3, an SF_6 synchronous circuit breaker has been manufactured. The technology derived from this development provided some of the basis for the initial design of the model interrupter shown in Figure 41.

Referring to this figure the left hand side of the drawing shows the interrupter in the open position while the right hand side shows the contacts closed.

The interrupter consists of a stationary contact assembly (item 1) which constitutes the throat and the diverging sections of a typical De-Laval nozzle. Also a part of this assembly is the high pressure seal which is located adjacent to the contacts.

The moving contact (item 2) serves a dual purpose; it is used as a blast valve and as the arcing contact. Whenever the interrupter is required to open an electrodynamic drive system is activated. The repulsion force generated initiates the motion of the contact and as the high pressure seal is broken the gas flow is established. The pressure front that appears across the face of the contact produces a pneumatic force which provides an assist in accelerating the contact towards its fully open position.

FIGURE 41 - 19mm MODEL INTERRUPTER
USING SF_6 GAS

A reset pressure applied to the underside of the moving contact plus the force created by the differential in sealing areas provides the needed force to maintain the interrupter contacts closed.

After the parting of the contacts an electric arc is established between the central tip of the moving contact and the lower end of the stationary contact. A combination of magnetic and pneumatic forces act upon the arc column and cause it to travel upwards along the sides of the diverging section of the nozzle until the arc is completely transferred to a catcher electrode (item 3) located at the exit of the nozzle.

The interrupter was designed to be operated at nominal upstream pressure of 1.9×10^6 Pascals (275 psig) and a downstream pressure of $.2 \times 10^6$ Pascals (30 psig). The nominal average opening velocity of this interrupter was 15 m/sec (50 ft/sec).

SHORT LINE FAULT INTERRUPTING TESTS

As stated earlier, previous experience has shown that the most difficult condition encountered by an SF_6 interrupter, following the interruption of a short line fault current, is imposed by the high rate of rise of recovery voltage (de/dt) that appears across the breaker terminals. This sensitivity of an interrupter to the rate of recovery voltage suggests that, for the purpose of establishing the limits of performance of an interrupter, one of the logical choices of a variable parameter is the de/dt . The other basic parameters selected that define the performance of the interrupter were: Upstream pressure and rate of decay of the fault current (di/dt).

The test method selected for these investigations was the direct synthetic test previously described in this report. With the exception that instead of the simulated short line fault network a resistor (R_a) and a capacitor (C_a), (Figure 42), connected in series were located across the test device. The characteristic transient voltage appearing across the R-C combination is described by an exponential function. It is then relatively simple to modify the initial slope of this exponential, (by merely changing the values of the resistor), to match the required rate of rise of recovery voltage.

When these two conditions are fulfilled the past arc history generally does not influence the performance of the interrupter (Reference 49, 50) and the direct synthetic test method can be used with a high level of confidence.

The short line fault interrupting tests were performed using sizes of nozzles 12mm, 19mm and 25mm. The interrupting limit was defined as the particular value of de/dt , at a constant pressure and di/dt , where at least two successful interruptions out of three attempts were observed. This procedure was repeated for different values of di/dt , and pressure.

The initial tests were performed using pure SF_6 as the interrupting medium. In later tests, and based on some past experience (Reference 2, 3), Nitrogen was added to the SF_6 . The mixture of SF_6 and N_2 was varied on a volume per cent basis and the interrupting performance of these mixtures at upstream pressures of 1.4×10^6 , (200 psig), 1.7×10^6 , (240 psig), and 1.9×10^6 pascals, (280 psig), was investigated for a 19mm nozzle diameter at a di/dt of 48 Amps/ μs .

The downstream pressure for all of these tests was $.1 \times 10^6$ pascals (15 psig) and an approximately constant arcing time of 0.9 ms was maintained throughout the tests.

The 12mm nozzle was tested using a 50% - 50% (by pressure) mixture of SF_6 and N_2 , at di/dt levels of 48, 31.6 and 26.8 Amps/ μs . The upstream pressures investigated were the same as the ones used for the 19mm nozzle.

The tests using the 25mm diameter nozzle were rather limited in number and only a few meaningful results were obtained with a di/dt of 48 Amps/ μs and pressures of 1.7×10^6 and 1.9×10^6 pascals.

Tables IX, X, XI and XII show in a tabular form the results obtained with a 19mm diameter nozzle by increasing the percentage of SF_6 in the mixture from 0% to 100% in steps of 25%. These results have been plotted and are shown in Figure 43.

The results obtained with a 12mm and a 25mm nozzle are shown in Tables XIII and XIV respectively.

FIGURE 43 - RATE OF RISE OF RECOVERY VOLTAGE VS. UPSTREAM PRESSURE FOR DIFFERENT MIXTURES OF N_2 AND SF_6

DISCUSSION OF RESULTS

The recovery voltage capabilities obtained with the tested models are considerably short of 22kV/μs.

The results, as shown in Figure 43, have verified earlier observations concerning the performance of an interrupter with mixtures of SF_6 and N_2 .

FIGURE 44 - MOVING CONTACT (TOP) AND STATIONARY CONTACT (BOTTOM) FROM 3/4 INCH SF₆ GAS INTERRUPTER

TABLE NO. IX

SYNCHRONOUS TRANSMISSION BREAKER

GAS MIXTURE = 100% N₂ - 0% SF₆

19mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	18.8	48	.9	F	2/.1	.35
16	18.5	48	.9	F	2/.1	.2
16	18.5	48	.9	F	2/.1	.16
16	18.5	48	.9	F	2/.1	

TABLE NO. X

SYNCHRONOUS TRANSMISSION BREAKERGAS MIXTURE = 75% N₂ - 25% SF₆19mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	19.7	48.5	.9	P	1.9/.1	.25
16	19.7	48.5	.9	F	1.9/.1	.34
16	19.7	48.5	.9	P	1.9/.1	.28
16	19.7	48.5	.9	P	1.6/.1	.28
16	19.7	48.5	.9	F	1.4/.1	.28
16	18.9	48.5	.9	F	1.9/.1	.32
16	19.4	48.5	.9	P	1.9/.1	.31
16	19.4	48.5	.9	P	1.9/.1	.31
16	19.4	48.5	.9	F	1.6/.1	.31
16	19.4	48.5	.9	F	1.6/.1	.31
16	19.4	48.5	.9	P	1.9/.1	.32
16	18.9	48.5	.9	F	1.9/.1	.34
16	19.0	48.5	.9	F	1.6/.1	.28
16	18.9	48.5	.9	P	1.6/.1	.25
16	18.95	48.5	.9	P	1.6/.1	.25
16	19.0	48.5	.9	F	1.4/.1	.25
16	19.0	48	.9	F	1.4/.1	.2
16	19.0	48.0	.9	P	1.4/.1	.17
16	19.0	48.0	.9	P	1.4/.1	.17
16	19.0	45.6	.9	F	1.4/.1	.2

TABLE NO. XI

SYNCHRONOUS TRANSMISSION BREAKER

GAS MIXTURE = 50% N₂ - 50% SF₆

19mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	19.0	48.5	.9	F	1.9/.1	.42
16	19.0	48.5	.9	P	1.9/.1	.35
16	18.5	46.8	.9	P	1.9/.1	.4
16	18.5	45.1	.9	P	1.9/.1	.4
16	17.7	45.1	.9	P	1.9/.1	.42
16	17.7	45.1	.9	F	1.9/.1	.45
16	17.7	46.8	.9	F	1.9/.1	.45
16	17.7	45.1	.9	P	1.6/.1	.34
16	17.7	46.8	.9	P	1.6/.1	.4
16	17.7	45.1	.9	P	1.6/.1	.37
16	17.7	48.0	.9	P	1.6/.1	.37
16	18.4	46.8	.9	P	1.6/.1	.4
16	18.4	46	.9	F	1.6/.1	.42
16	18.4	46	.9	P	1.4/.1	.28
16	18.4	45	.9	F	1.4/.1	.34
16	18.5	45	.9	F	1.4/.1	.31
16	18.9	44	.9	F	1.4/.1	.28
16	18.5	46	.9	P	1.4/.1	.25
16	18.4	47.5	.9	P	1.4/.1	.25

TABLE NO. XII

SYNCHRONOUS TRANSMISSION BREAKER

GAS MIXTURE = 25% N₂ - 75% SF₆

19mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	18.5	47.3	.9	F	1.9/.1	.48
16	18.5	46	.9	F	1.9/.1	.45
16	18.5	46.8	.9	F	1.9/.1	.45
16	18.5	46.8	.9	P	1.9/.1	.42
16	18.5	46.8	.9	F	1.6/.1	.37
16	18.5	48	.9	P	1.6/.1	.31
16	18.5	48.5	.9	P	1.6/.1	.34
16	18.5	48.5	.9	F	1.6/.1	.34
16	18.9	48.5	.9	F	1.6/.1	.31
16	18.9	49.5	.9	P	1.6/.1	.3
16	18.9	47.7	.9	F	1.6/.1	.3
16	19.4	47.7	.9	P	1.4/.1	.17
16	18.9	48	.9	P	1.4/.1	.2
16	19.0	48.5	.9	F	1.4/.1	.22
16	18.9	46.8	.9	P	1.4/.1	.22
16	18.9	48.5	.9	P	1.4/.1	.2
16	18.9	48.5	.9	P	1.6/.1	.28
16	18.9	48.5	.9	P	1.6/.1	.28
16	18.9	48.5	.9	P	1.9/.1	.4
16	18.5	48	.9	P	1.9/.1	.37
16	18.9	48.5	.9	P	1.9/.1	.42

TABLE NO. XIII

SYNCHRONOUS TRANSMISSION BREAKER

GAS MIXTURE = 0% N₂ - 100% SF₆19mm Nozzle Diameter

E _o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	17.4	44	.9	P	1.9/.1	.4
16	17.7	44.4	.9	P	1.9/.1	.45
16	19.3	46.8	.9	F	1.9/.1	.45
16	17.8	43.6	.9	F	1.9/.1	.48
16	17.7	48.5	.9	P	1.9/.1	.42
16	18.5	46.8	.9	F	1.9/.1	.42
16	16.9	43.6	.9	P	1.9/.1	.4
16	19.4	47.7	.9	P	1.9/.1	.4
16	19.4	48.5	.9	F	1.9/.1	.42
16	19.4	48	.9	F	1.6/.1	.4
16	19.4	48.5	.9	F	1.6/.1	.35
16	19.4	48.5	.9	P	1.6/.1	.28
16	19.4	48	.9	F	1.6/.1	.31
16	19.4	47.7	.9	F	1.6/.1	.31
16	19.4	48	.9	P	1.6/.1	.28
16	19.4	45.1	.9	F	1.4/.1	.2
16	19.4	45.1	.9	P	1.4/.1	.17
16	18.9	47.7	.9	P	1.4/.1	.2
16	19.2	48	.9	F	1.9/.1	.4
16	18.7	48.5	.9	F	1.9/.1	.35
16	18.7	46.8	.9	P	1.9/.1	.34
16	18.5	47	.9	P	1.9/.1	.34
16	18.5	48.5	.9	F	1.9/.1	.37

TABLE NO. XIV
SYNCHRONOUS TRANSMISSION BREAKER
GAS MIXTURE - 50% SF₆ - 50% N₂

12mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	18.9	46.7	.95	F	1.9/.1	-
16	19.4	46.7	.85	F	1.9/.1	-
16	16.0	40.8	.85	F	1.9/.1	-
16	8.8	20.7	1.15	P	1.9/.1	-
16	12.6	30.0	.8	F	1.9/.1	-
16	8.8	21	1.2	P	1.9/.1	-
16	8.8	21	1	P	1.9/.1	-
16	8.4	21	1.2	P	1.9/.1	-
16	10.7	26.8	.85	P	1.9/.1	.29
16	10.7	26.8	.75	P	1.9/.1	.35
16	10.7	26.8	.75	F	1.9/.1	.45
16	10.7	26.8	.75	F	1.9/.1	.41
16	10.7	28.7	.9	P	1.9/.1	.38
16	10.7	26.8	.8	F	1.9/.1	.38
16	10.9	26.8	.8	F	1.9/.1	.35
16	10.5	26.3	1.2	P	1.9/.1	.33
16	10.9	26.8	.8	P	1.6/.1	.3
16	10.7	26.8	.8	F	1.6/.1	.31
16	10.9	26.8	.9	F	1.6/.1	.3
16	10.7	26.8	.85	F	1.6/.1	.29
16	10.5	26.8	.8	P	1.6/.1	.27
16	10.5	26.8	.75	F	1.6/.1	.27
16	10.7	26.8	1.2	P	1.6/.1	.25
16	10.7	26.8	.75	P	1.4/.1	.15
16	10.9	26.6	.85	P	1.4/.1	.18
16	10.7	26.7	.8	P	1.4/.1	.21
16	10.7	26.8	.7	P	1.4/.1	.23

TABLE NO. XIV (Continued)
 SYNCHRONOUS TRANSMISSION BREAKER
 GAS MIXTURE - 50% SF₆ - 50% N₂
12mm Nozzle Diameter

E _o (kV)	$\hat{I}$ (kA)	di/dt (A/μs)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/μs)
16	10.7	26.8	.8	P	1.4/.1	.24
16	10.7	26.8	.75	F	1.4/.1	.3
16	10.7	26.8	.8	F	1.4/.1	.27
16	10.7	27.4	.75	F	1.4/.1	.25
16	10.7	27.4	.85	F	1.4/.1	.25
16	10.5	26.3	.8	F	1.4/.1	.24
16	10.5	27.1	.8	F	1.4/.1	.23
16	10.7	28.0	.8	P	1.4/.1	.21
16	12.6	32.4	.8	F	1.4/.1	.19
16	12.2	31.6	.85	F	1.4/.1	.11
16	12.2	32.4	.85	P	1.4/.1	.11
16	12.2	31.6	.85	P	1.4/.1	.13
16	12.2	31.6	.8	P	1.4/.1	.15
16	-	31.6	-	F	1.4/.1	.19
16	11.8	-	.75	P	1.4/.1	.17
16	12.2	31.2	.8	F	1.4/.1	.17
16	12	29.4	1.2	F	1.4/.1	.15
16	12	31.6	.8	P	1.4/.1	.15
16	12.2	31.2	.8	F	1.6/.1	.22
16	12	31.6	.8	P	1.6/.1	.19
16	12	32.4	.8	P	1.6/.1	.2
16	12	-	.9	P	1.6/.1	.19
16	11.4	-	.9	P	1.9/.1	.24
16	11	-	1	P	1.9/.1	.28
16	10.6	-	.95	P	1.9/.1	.32
16	10.5	-	.95	P	1.6/.1	.24

TABLE NO. XIV (Continued)
SYNCHRONOUS TRANSMISSION BREAKER
GAS MIXTURE - 50% SF₆ - 50% N₂
12mm Nozzle Diameter

E_o (kV)	$\hat{I}$ (kA)	di/dt (A/ μ s)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/ μ s)
16	11.4	31.4	.95	F	1.9/.1	.24
16	11.4	31.4	.8	F	1.9/.1	.22
16	11.4	-	.95	P	1.9/.1	.2
16	11.4	-	1	F	1.9/.1	.2
16	11.4	-	.95	F	1.9/.1	.2
16	11.8	-	-	F	1.9/.1	.19
16	12	33.2	1	F	1.9/.1	.2
16	12	31.6	.95	P	1.9/.1	.19
16	11.8	31.6	1.2	P	1.9/.1	.19
16	11.8	31.6	1.2	P	1.9/.1	.19

TABLE NO. XV
 SYNCHRONOUS TRANSMISSION BREAKER
 GAS MIXTURE = 50% SF₆ - 50% N₂
 25mm Nozzle Diameter

E _o (kV)	$\hat{I}$ (kA)	di/dt (A/μs)	ARCING TIME (ms)	PASS OR FAIL	HP/LP MEGA PASCALS	de/dt (kV/μs)
16	20.2	48.5	.9	F	1.6/.1	.36
16	20.2	48.5	.9	F	1.6/.1	.34
16	20.2	49.5	.9	F	1.6/.1	.34
16	20.2	50.2	.9	P	1.6/.1	.28
16	20.2	48.5	.9	P	1.6/.1	.31
16	20.2	48.5	.9	P	1.6/.1	.31
16	20.2	49.5	.9	F	1.6/.1	.34
16	20.2	48.5	.9	P	1.9/.1	.39
16	20.2	-	.9	P	1.9/.1	.45
16	20.2	48.5	.9	P	1.9/.1	.51
16	20.2	-	.9	F	1.9/.1	.56
16	20.2	48.5	.9	F	1.9/.1	.54
16	20.2	-	.9	F	1.9/.1	.54
16	20.6	-	.9	F	1.6/.1	.34
16	20.6	-	.9	P	1.6/.1	.28
16	20.6	50.5	.9	P	1.6/.1	.31
16	20.6	-	.9	P	1.6/.1	.31
16	20.6	51.5	.9	P	1.6/.1	.34
16	20.6	50.5	.9	P	1.6/.1	.36
16	20.6	50.5	.9	F	1.6/.1	.39
16	20.6	50.5	.9	F	1.6/.1	.39
16	20.2	48.5	.9	F	1.6/.1	.36
16	20.6	49.5	.9	P	1.6/.1	.36
16	20.6	50.5	.9	F	1.6/.1	.39

It is evident that the recovery capability of the interrupter is increased when certain percentages of N_2 are added to the SF_6 . (Reference 51). It is observed that the increase can be as much as a factor of approximately 1.4 when a 50 - 50 mixture, by pressure/volume, of N_2 and SF_6 is used. However, even under this improved condition, at a di/dt of 48 Amps/ μs , (which corresponds to a 90% short line fault) a maximum dv/dt of approximately 420 volts/ μs was obtained using a nozzle having a diameter of 19mm, and at an upstream pressure of 1.9×10^6 pascals (280 psi).

The data obtained with the 12mm nozzle suggests that clogging of the nozzle was likely when a di/dt of 48 Amps/ μs was attempted. However, increasing the nozzle diameter to 25mm did not result in a definite and sizeable increase in the interrupting capability of the model.

The results obtained with all of the nozzles tested demonstrated that the dv/dt capability of an interrupter is a function of the upstream pressure raised to a power, which has been calculated as approximately 1.5.

$$dv/dt \propto p^{1.5}$$

The results obtained with this series of tests clearly identified the necessity of a sizeable improvement in performance. The same results also serve to point out two possible alternatives for effecting such improvement.

- a) increase the nozzle diameter
- b) increase the upstream pressure

In addition to the two options listed above at least one other possible solution to the problem can be investigated. That is the addition to the interrupter of external passive elements such as resistors or capacitors designed to modify the inherent transient recovery of the system.

FIGURE 45 - INTERRUPTING TEST 1.93×10^6 PASCALS
 50% SF₆ - 50% N₂ GAS MIXTURE
 I = 8420 A/DIV
 E(ARC) = 132.4 V/DIV
 T = 500 ms/DIV

FIGURE 46 - INTERRUPTING TEST 1.93×10^6 PASCALS
 50% SF₆ - 50% N₂ GAS MIXTURE
 I = 210.5 A/DIV
 E(TRV) = 3340 V/DIV
 T = 5 μ S/DIV

INCREASE IN NOZZLE DIAMETER

The modest increase in performance that was observed during the tests with the 25mm nozzle over the smaller 19mm nozzle remains questionable due to the small number of valid data points. Nevertheless, experience has shown that higher performance is obtained from SF_6 interrupters when the nozzle diameter is increased. However, it is rather obvious that an increase in the size of the nozzle will result in an increase in size not only of the interrupter but of the operating mechanism and the overall breaker somewhat defeating one of the objectives of the project.

It is also unlikely that by only changing the nozzle diameter the dv/dt capability will be improved to the desired values. Furthermore, some evidence exists, (Reference 52), to relate the effect of a change in nozzle area and interrupter capability. This reported observation seem to indicate that a limit can be reached where any further increases of the nozzle area will not result in improved dv/dt performance.

This possible mode of action for improving the performance of the interrupter should therefore be considered only when the possibility of clogging is likely or as a complementary aid to other methods.

INCREASE IN UPSTREAM PRESSURE

The exponential relationship between the dv/dt capability and the upstream pressure of an SF_6 interrupter has been fairly well documented for the gaseous phase of SF_6 . Assuming that the exponential relationship holds beyond the critical pressures, and into the fluid phase of SF_6 , an increase in the upstream pressure of the interrupter appears to be a logical choice.

It has been demonstrated that a 50 - 50% mixture of SF_6 and N_2 gives an improved performance. It has also been reported that the dependence of the dv/dt and the upstream pressure of the mixture basically remains the same as if pure SF_6 was used; Therefore, the mixture of the two gases would appear to be an attractive possibility. When an upstream pressure of 10.3×10^6 pascals (1500 psig) is considered the equivalent dv/dt for a 19mm nozzle diameter are:

Pure SF_6 $\approx$ 4.3kV/ μ s

50/50% mixture $\approx$ 5.1kV/ μ s

This implies that even at these high pressures the interrupter performance is short of its goal. Furthermore, in the case of a mixture part of the SF_6 will be in its liquid phase while the N_2 is still as a gas. This condition then precludes the possibility of using the gas mixtures at the higher pressures.

It becomes apparent then that an increase in pressure alone would not yield the needed improvement unless this pressure is raised to values of approximately 34.4×10^6 pascals, (5000 psig).

This pressure is judged excessive and beyond acceptable limits. Therefore the feasibility of increasing the pressure to 10.3×10^6 to 13.8×10^6 pascals, (1500 - 2000 psig), coupled with an small increase in the nozzle diameter and the addition of TRV modifying components should be considered.

TRV MODIFICATIONS

An accepted practice throughout the industry, for the purpose of TRV modification, is the use of shunt capacitors across the interrupter contacts.

It has been demonstrated (Reference 53) that by adding a capacitor in parallel to the interrupter contact the linearly-rising recovery voltage is effectively delayed for a short period of time, sufficient to allow the SF_6 to recover its conductance, thus making the interrupter capable of withstanding the ensuing TRV.

Since the time constant obtained with the addition of a capacitor is equal to the Z (the surge impedance) times C (the external capacitance), the size of the capacitance becomes the limiting function.

Whenever additional modification of the TRV is desired the use of a shunt resistor or a R-C combination can be considered.

A resistor, as well as a capacitor, are effectively connected in parallel with the surge impedance of the faulted line. The resistor unlike the capacitor will dissipate energy and will lower the peak of the voltage produced by the travelling wave without changing the time to crest. The change in voltage

magnitude is inversely proportional to the ratio of the surge impedance (Z) to the equivalent impedance of the shunt resistor. The use of a resistor equal to the value of the surge impedance thus reduces the initial rate of rise of voltage to half of its unmodified value.

If the performance of the interrupter tested was to be increased solely by the use of TRV modification our calculations showed that a combination of a 10nf capacitor in parallel with a 12.5 ohms resistor would be required. The practicality of such a resistor is questionable when the thermal requirements and its physical size are considered.

For a non linear resistor, made of iron, the final resistance would be 105 ohms, at a temperature of 789°C. The physical dimensions of this resistor would be:

wire length = 688 meters

wire gauge = AWG 9

Obviously the limitations imposed by such a resistor clearly indicate the need for improving the basic performance of the interrupter and again to the likelihood of using a combination of methods for obtaining the required performance of the interrupter.

2.4.4 INVESTIGATIONS WITH LIQUID SF₆

As it was previously concluded, an increase in the upstream operating pressure, coupled with changes in the nozzle dimensions, and the addition of TRV modifying elements would be required to improve the capability of the interrupter.

The increase in pressure required is such that the critical pressure point of SF₆ will be exceeded, and therefore, the interrupter will operate with SF₆ in the fluid phase.

The success of this method for improvement of performance depends upon the validity of the assumption that no discontinuity at higher pressures, beyond the critical pressure point of SF₆, would be found in the recovery voltage and pressure relationship earlier established for SF₆ up to pressures of 2.1×10^6 pascals.

The basic design of the model previously used was revised to render it adequate for operating at higher pressures, up to 10.3×10^6 pascals. The revision consisted primarily of an outside enclosure for the interrupter, to limit the high pressure volume, and to reduce the inside diameter of the surface exposed to the high pressures for an effective reduction of the end loading forces. The contact structure was maintained, resembling as closely as possible the original design. Major changes were made in the design of the high pressure main seal. These changes were implemented after a great deal of effort was devoted to obtaining a positive and reliable high pressure seal design. A description of this design is provided later in the report.

A limited number of S.L.F tests were performed using this model interrupter and a tabulation of the results are shown in Table XVI.

A typical set of tests records is included as Figures 47 and 48. All the tests were made with the same test set-up previously used for the investigations of SF_6 gas and gas mixtures.

The test results indicate that a significant increase in the interrupting performance is obtained with the increase in pressure. It is readily seen that a five fold increase in pressure yielded an increase in the dv/dt capability of almost one order of magnitude. It is further observed that using the pressure raised to the 1.5 power relation the calculated dv/dt equals 3.9kV/ μs while the tested capability appears to be between the passing value of 3.9kV/ μs and the failure point obtained at 4.5kV/ μs .

The results obtained in this series of interrupting tests have served to demonstrate that an increase in upstream pressure is related to an increase in the dv/dt capability by a 1.5 exponent. Making use of this fact and other additional relationships presented in Reference 52 it is possible to determine the approximate interrupter design parameters required for satisfying the project specifications.

It is estimated that by enlarging the nozzle diameter to 32mm (1.25 in) and utilizing an upstream pressure of 13.8×10^6 pascals it will be possible to obtain a dv/dt capability of approximately 18kV/ μs at a di/dt of 48 Amps/ μs . This optimum performance is highly desirable because the value of TRV modifying components required will be minimized. Nevertheless, an increase in the

TABULATION OF DATA - TABLE NO. XVI

SYNCHRONOUS TRANSMISSION BREAKER

LIQUID SF₆

TEST NO.	TYPE TEST	E _o kV	$\hat{I}$ kA	R _a Ω	C _a μ f	PASS OR FAIL	di/dt A/ μ s	de/dt kV/ μ s	HP PRESSURE 1 x 10 ⁶ PASCALS
9	OPEN	17	21.2	200	5.12	F	52	8.7	9.65
10	OPEN	17	21.2	150	5.12	F	51	6.6	10.3
15	OPEN	17	21.2	100	5.12	F	51	4.5	10.3
46	OPEN	17	21.2	75	5.12	P	51	3.4	10.3
47	OPEN	17	21.2	75	5.12	P	53	3.4	10.3
48	OPEN	17	21.2	85	5.12	P	-	3.9	10.3
49	OPEN	17	21.2	100	5.12	F	51	4.5	10.3
51	OPEN	17	21.2	150	5.12	P	-	5.0	10.3
52	OPEN	17	21.2	250	5.12	P	41	8.2	10.3

FIGURE 47 - INTERRUPTING TEST 1.03×10^{-7} PASCALS SF_6

I = 8160 A/DIV
 E(ARC) = 243 V/DIV
 T = 500 μs /DIV

FIGURE 48 - INTERRUPTING TEST 1.03×10^{-7} PASCALS SF_6

I = 510 A/DIV
 E(TRV) = 2425 V/DIV
 T = 5 μs /DIV

dv/dt capability to any level equal to or greater than 10kV/ μ s will permit the use resistors and/or capacitors, of reasonable physical dimensions to accomplish the final objective. If for example, a reduction of 50% in the TRV is required and a resistor alone is used, the ohmic value of it will be 360 ohms. This value of resistance is not uncommon in many present circuit breaker designs and therefore the design could easily be adapted for this application.

ARC VOLTAGE IN LIQUID SF₆

To gain additional knowledge on the behavior of liquid SF₆ under arcing conditions and to determine the general order of magnitude that can be expected for the arc voltage, a series of experimental measurements were made.

The test set-up is shown in Figure 49. It consisted of a pair of Cu-W electrodes, 12mm in diameter held vertically inside the arc chamber. The arc chamber was an aluminum cylinder 50mm in diameter and 250mm long that served as the return path for the current thus providing a coaxial arrangement to minimize the effects of the magnetic fields upon the arc. Both the lower electrode, which was the moving contact, and the arc chamber were electrically grounded for these tests.

The parameters measured in these tests were: Arc currents in the range of 200 to 2500 Amperes rms; SF₆ pressures of $.2 \times 10^6$ pascals up to 6.9×10^6 pascals (30 to 1000 psi) and contact gaps of 6.4mm; 19mm and 50mm.

The test procedures were rather simple. For a given contact separation a few timing test were made to determine the point of contact part. The arc chamber was filled with SF₆ to the required pressure and an arc was drawn across the electrodes.

The complete tabulation of the results is given in Table XVII. In this table; g is the contact gap, p_o the initial chamber pressure, Δp is the measured pressure increase due to the arc, I is the rms value of the test current, V is the measured arc voltage, and a column for the calculated arc voltage V_c has been added. This calculated arc voltage (V_s) is defined as the arc voltage which would have been measured if the arcing chamber's pressure had been kept at the initial pressure (p_o).

FIGURE 49 - LIQUID SF₆ ARC VOLTAGE TEST SET-UP

TABULATION OF DATA - TABLE NO. XVII

g mm	P_o 1×10^6 Pascals	Δp 1×10^6 Pascals	$P_o + \Delta p$ 1×10^6 Pascals	I Amp. RMS	V Volts	V_c Volts	CURRENT LOOP MEASURED	TEST No.
6.4	1.86	0 (E)	1.86	218	48.6	48.6	#3	38
6.4	1.86	0 (E)	1.86	313	45.1	45.1	3	39
6.4	1.86	0.014 (E)	1.874	799	40.5	40.5	3	34
6.4	1.86	0.014 (E)	1.874	821	42.3	42.2	3	33
6.4	1.86	.041	1.901	1173	35.3	35.1	3	35
6.4	1.86	.041	1.901	1458	31.7	31.5	3	37
6.4	1.86	.083	1.943	1460	33.5	33.1	3	36
19	.207	.007	.214	336	58.9	58.4	4	85
19	.207	.007	.214	337	56.2	55.7	4	84
19	.207	.007 (E)	.214	344	58.1	57.6	3	67
19	.207	.032	.239	906	63.1	60.8	4	82
19	.207	.032 (E)	.239	907	61.5	59.2	5	81
19	.207	.062	.269	2409	63.1	59.0	5	73
19	.207	.069	.276	2438	65.3	60.6	5	74
19	1.03	.014	1.044	336	82.9	82.6	4	86
19	1.03	.017	1.047	336	89.9	89.5	4	87
19	1.03	.021	1.051	905	87.2	86.8	4	80
19	1.03	.041	1.071	930	89.9	89.0	4	78
19	1.03	.096	1.126	2453	82.9	81.0	4	76
19	1.03	.120	1.15	2453	80.3	78.0	4	75
19	2.76	.055 (E)	2.815	336	104.2	103.7	5	89
19	2.76	.055 (E)	2.815	336	123.1	122.9	4	90
19	2.76	.083 (E)	2.843	907	110.8	109.9	4	91
19	2.76	.083	2.843	907	117.7	116.8	4	92
19	2.76	.165	2.925	948	126.3	124.4	4	93
19	2.76	.62 (E)	3.38	2475	130.5	123.8	4	94
19	2.76	.689 (E)	3.449	2475	137.0	129.2	4	95
19	4.13	.193	4.323	345	128.4	126.9	5	100
19	4.13	.193	4.323	350	130.5	129.0	5	99

TABULATION OF DATA - TABLE NO. XVII (Continued)

g mm	p_o 1×10^6 Pascals	Δp 1×10^6 Pascals	$p_o + \Delta p$ 1×10^6 Pascals	I Amp. RMS	V Volts	V_c Volts	CURRENT LOOP MEASURED	TEST No.
19	4.13	.537	4.667	930	119.8	116.1	#5	106
19	4.13	.441	4.571	939	105.9	103.2	5	105
19	4.13	.565	4.695	939	128.4	124.2	5	107
19	4.13	1.722(E)	5.852	2446	134.8	123.1	5	102
19	4.13	2.067(E)	4.197	2519	158.4	142.6	5	103
19	6.82	.131	6.951	350	123.1	122.8	5	110
19	6.54	.441	6.981	948	108.1	107.7	5	108
19	6.89	2.19	9.08	2446	171.2	159.3	4	113
50	.207	.303	.510	846	156.1	123.6	11	177
50	.207	.365	.572	870	156.1	120.0	11	176
50	.207	.813	1.020	2379	175.7	116.0	11	183
50	.207	.772	.979	2393	174.5	116.5	11	182
50	1.03	.158	1.188	390	229.2	220.9	7	185
50	1.03	.482(E)	1.512	828	209.7	189.8	8	179
50	1.03	.413	1.443	846	214.5	196.6	7	178
50	1.03	1.922	2.952	2353	232.1	176.6	9	181-A
50	1.03	1.309	2.339	2389	215.5	174.2	7	181-B

NOTES: g : Contact Separation
 p_o : Initial Arc Chamber Pressure
 Δp : Pressure Increase
 I : Arc Current
 V : Measured Arc Voltage (@ $p = p_o + \Delta p$)
 V_c : Calculated Arc Voltage (@ $p = p_o$)
 E : Estimated Value

The tabulated results have been used to plot the graphs of measured arc voltage (V) against the equivalent pressure $p_0 + \Delta p$; of the calculated arc voltage (V_c) against the current I ; and of the pressure increase Δp against the arc energy input shown in Figures 50, 51 and 52 respectively.

From the figures it can be observed that:

- a) The dependence of the arc voltage upon the current (Figure 51) is not very pronounced, at least in the range of currents investigated. For pressures below the SF_6 vapor pressure (2.4×10^6 pascals @ 27°C) the trend of a decreasing arc voltage with increasing current could be observed. At higher pressures no such trend was observed. Instead, the arc voltage exhibited a tendency to initially decrease as the current was increased then followed with an increase of arc voltage with corresponding increases in current.
- b) It is observed, Figure 50, that the arc voltage increases exponentially with respect to pressure. This increase with pressure can be approximated by the following relationship:

$$V \propto p^{0.26}$$

The increase with pressure is observed over the full range of pressures tested including the liquid SF_6 state. This continuity in the pressure relationship is not surprising when one compares the magnitudes of heat of vaporization to the dissociation energy or the ionization energy of SF_6 .

The curve showing the results taken from Reference 54 indicate that the arc voltage had a somewhat higher exponential power. However, it should be noted that

FIGURE 50 - ARC VOLTAGE (V) VS. EQUIVALENT PRESSURE ($P_0 + \Delta P$)

FIGURE 51 - ARC VOLTAGE VS. CURRENT

FIGURE 52 - PRESSURE INCREASE VS. ENERGY INPUT

the pressure increase due to arcing had not been taken into consideration. But in any event, the results obtained in the tests appear to be in general agreement with those published in Reference 54.

- c) The average electric field strength can be easily calculated at different pressures. The values obtained at $.69 \times 10^6$ pascals (100 psi) were 38 and 33 volts per cm for gaps of 19 and 50mm respectively. These electric gradients are low compared with the values of 63 volts per cm reported in Reference 54. This discrepancy may partially be explained by the possibility of looping of the arc. A combination of a bigger arc chamber (127mm in Reference 54 vs. 50mm in our tests), larger contact gaps (76mm vs. 50mm or less) lower values of current and the effects of external magnetic fields would tend to extend the arc and therefore the gradient of 63 V/cm reported may actually be somewhat smaller.

SINGLE PRESSURE LIQUID SF_6 INTERRUPTER

In some of the tests performed during the arc voltage investigations it was observed that the arc was readily extinguished at current zero. Having a 50mm gap, as the pressure was increased from $.34 \times 10^6$ to 2.8×10^6 pascals, all currents in the range of 372 to 2571 amperes were interrupted.

To further explore the interrupting capability of an interrupter when no axial gas blast is used, and to further examine the arc voltages produced when a self generated gas flow takes place a series of current interruption tests was planned.

It was decided that one expedient way to obtain the information being sought was to use a standard oil interrupter pot and immerse it in liquid SF_6 .

The interrupter assembly used was a standard production unit used by I-T-E on breakers rated at 34.5kV and with an interrupting rating of 36kA. An outline of the interrupter is shown in Figure 53.

It was reasoned that the interrupting process in a static liquid SF₆ container would be similar to the process in oil. And therefore it was expected that some valuable information could be gained from these tests.

A total of seven interruptions were attempted at an initial average pressure of 6.4×10^6 pascals (930 psi) except for the last test where the initial pressure was only 4.1×10^6 pascals (600 psi). The currents attempted to interrupt ranged from 10kA to 60kA. The driving voltage in these tests was 4.5kV rms.

The initial tests were made with a contact gap of 86mm and at current values of 10 and 20kA. No successful interruptions were obtained under this condition.

With a contact gap of 137mm the device successfully interrupted 18.3kA and 35.3kA. It failed to interrupt at 60kA, it is believed that this failure occurred because of mechanical problems rather than by exceeding the device's capability. Furthermore, for this test a leak had developed in the interrupter and the initial pressure was considerably reduced. (4.1×10^6 pascals). The condition of the parts (Figures 54 and 55) after the tests revealed that severe damage occurred during the final test. It is also possible to observe in the test records that the contact opening time increased by approximately 20 ms; thus, suggesting the possibility of jamming the contacts.

The arc voltage observed during these tests was approximately twice the value previously reported as being obtained with a free burning arc. However, it must be remembered that, in the present test, the effective arc length is increased considerably by the blowout action of the explosion chamber and the escaping gas through the splitter plates. It is therefore difficult to ascertain what was the effective arc length to be used in the calculation of the arc voltage gradient.

FIGURE 53 - SINGLE PRESSURE LIQUID SF_6 INTERRUPTER

FIGURE 54 - SINGLE PRESSURE LIQUID SF₆ INTERRUPTER TEST PARTS AFTER COMPLETION OF TESTS

FIGURE 55 - SINGLE PRESSURE LIQUID SF₆ INTERRUPTER TEST PARTS AFTER COMPLETION OF TESTS

As it is shown in the tabulation of the results (Table XVIII), the pressure rise resulting from the arc energy is very substantial and should be carefully evaluated if any consideration to this type of design is considered.

The pressure build-up is observed to take place a considerable time after contact part thus precluding the use of this type of interrupter for a fast acting device such as a synchronous circuit breaker. The time lag in pressure rise is easily understood since it is attributed to the build-up of the energy input required to dissociate the SF_6 .

2.4.5 COMPARISON OF PERFORMANCE

VACUUM VS. SF_6

To embark on Phase II of the project it is necessary to make a comparative evaluation of the performances obtained with the vacuum and the SF_6 interrupters.

The criteria for the selection of the concept that is to be pursued will be based primarily in consideration of the transient recovery voltage capability exhibited by the interrupters. This recovery capability must be evaluated in the thermal as well as in the dielectric recovery regions.

The possibility of using a gaseous SF_6 interrupter has been discarded since the results obtained with the models tested were quite short of meeting the basic voltage recovery requirements. Liquid SF_6 and vacuum interrupters therefore become the available options to be considered for future development.

Although, with a liquid SF_6 interrupter, no test data was obtained to demonstrate its recovery capability following the interruption of a terminal fault, it is known from previous experience that at an expected intermediate pressure of 2.8×10^6 pascals (400 psi) and a minimum contact gap of 25mm, (1 inch) the inherent capability of the interrupter should be in excess of 400kV and therefore it is greater than the maximum requirement of the original specifications of the interrupter.

TABULATION OF DATA - TABLE NO. XVIII

SYSTEM VOLTAGE kV, RMS	CONTACT STROKE mm	[4] CURRENT kA, RMS	[1] ARC VOLTAGE VOLTS	INITIAL PRESSURE 1×10^6 PASCALS	[2] MAXIMUM PRESSURE RISE 1×10^6 PASCALS	[3] PRESSURE AFTER TEST 1×10^6 PASCALS	ARCING TIME ms	ARC INTERRUPTION
4.43	85.8	~10	~548	6.41	3.27	6.89	16.2	Fail
4.43	85.8	~10	621	6.75	2.46	6.89	18.6	Fail
4.43	85.8	~20	1168	6.82	>4.13	7.30	12.9	Fail
4.43	85.8	17.0	913	6.61	>4.13	-	>21.0	Fail
4.43	136.7	18.3	767	6.20	6.38	-	12.6	Pass
4.43	136.7	35.3	1058	5.65	11.37	-	13.0	Pass
4.43	136.7	59.7	1570	4.13	10.68	5.51	7.2	Fail

- [1] Arc voltage measured at the current peak of the last current loop before interruption or, in cases of failing to interrupt, before the current was cut off by resistor breaker.
- [2] Occurred at the time of current interruption or current cut off. Four pressure relief valves set at 13.8×10^6 pascals were installed in the top plate of arcing chamber.
- [3] Pressure gauge reading, obtained a few minutes after test.
- [4] The maximum gap between arcing contacts are about 44.5mm and 95.2mm for 85.8mm and 136.7mm stroke, respectively.

The voltage withstand capability of a vacuum interrupter to a simulated 1-cos voltage envelope was discussed earlier in this report. It was stated then that in the absence of any prior arcing period the interrupter was capable of holding a peak voltage of 150kV and a gap breakdown occurred at a 160kV crest. Further testing revealed that a maximum of 86.5kV was withstood by a vacuum interrupter following the interruption of an arc.

The results imply that considering the unavoidable uneven distribution of voltage that appears across a series of interrupters, and the degradation in performance that results as consequence of an arc being present in the interrupters, it is reasonable to expect that a minimum of four (4) vacuum interrupters in series would be required for a 145kV rating using commercially available 15kV vacuum interrupters.

A tabulation of the assumed number of interrupting breaks required for different voltages is presented below in Table XIX.

TABLE XIX

VOLTAGE CLASS. kV	NO. OF VACUUM INTERRUPTERS	NO. OF SF ₆ INTERRUPTERS
145	4	1
362	8	2
800	16	4

A comparison of the dv/dt and di/dt relationships of both interrupters, liquid SF₆ and vacuum, is presented graphically in Figure 56. Curve A represents the results obtained with the vacuum interrupter when tested by the direct synthetic method. As it was discussed previously this method of testing, when applied to vacuum interrupters, produces optimistic results due to the probability that under these tests conditions a diffused arc is maintained and therefore the maximum capability was realized on the interrupter.

FIGURE 56 - COMPARISON OF INTERRUPTER CAPABILITY

Curve B represents the performance obtained with a liquid SF₆ interrupter model having a 19mm nozzle diameter. Curve C shows the estimated expected performance of a liquid SF₆ interrupter operated at 13.8×10^6 pascals and having a 32mm (1.25 in) nozzle diameter.

Based on these results it is evident that a better performance is obtained with a liquid SF₆ interrupter than with a vacuum interrupter. Furthermore, the need for a larger number of vacuum interrupters in series results in a more complicated and larger breaker assembly.

The high interrupting current requirements can not be met with the vacuum interrupters available at the present time, and therefore, it will necessitate an extension in the state of the art in the vacuum interruption technology, which is clearly beyond the scope of this project. However, the eventual utilization of vacuum interrupters in a synchronous breaker scheme can not be excluded. As new technology develops it is likely that higher voltage on interrupting ratings will be achieved. These newly developed vacuum interrupters may then overcome the disadvantages and limitations found in the designs tested.

Based on the mentioned observations a choice of an interrupter for Phade II of the project was made in favor of the liquid SF₆ model tested.

PART III

PHASE II

3.1 INTRODUCTION

The experimental results obtained to this date, using vacuum and SF₆ model interrupters, provided the basis for electing an interrupting media as the one offering the greatest probability of success. It has been demonstrated that by increasing the upstream pressure of an SF₆ interrupter, a proportional increase in performance can be expected. Furthermore, it was the general consensus that a fewer number of interrupters in series is needed when SF₆ interrupters are used instead of vacuum interrupters.

Having made a choice in favor of a high pressure (liquid) SF₆ interrupter, the interrupting ability of the chosen design must now be demonstrated.

In Phase II of the project the efforts were concentrated in designing an interrupter according to the findings and conclusions reached in Phase I. The new model was evaluated in terms of its mechanical performance, and its capability for meeting the electrical specifications that were set-forth at the initiation of the project.

From the results obtained in the Phase I investigations, both theoretical and experimental, it was claimed that at a di/dt of 48 A/μs a dv/dt capability of approximately 18kV/μs can be expected of a new design that incorporates an enlarged nozzle diameter, (31.8mm), and a higher operating pressure, (14 x 10⁶ Pascals (2000 psi)). However, several assumptions had been made in arriving at this expected performance which can be judged as being the most optimistic condition. Should some of the assumptions made be incorrect the performance level will naturally be different. In any event a goal has been set that a minimum capability of 10kV/μs will be required of the interrupter if its performance is to be judged acceptable.

The demonstration of the performance of the new interrupter model then was the primary object of Phase II. In addition to the interrupting investigations testing was done to establish the performance of the interrupter in such areas as: Momentary currents, continuous currents, dielectric withstand and mechanical operation.

3.2 DESIGN SUMMARY OF THE MODEL INTERRUPTER

Before proceeding with the detail analysis of the interrupter design it seemed appropriate that the fluid flow characteristics of SF_6 be evaluated.

The primary object of this analysis was to determine the time that is required to establish steady state flow corresponding to the instantaneous pressure distributions in the interrupter under no arc conditions.

The no arcing condition was selected in an effort to simplify the already complicated problem presented by the flow of liquid SF_6 . Another simplification was made by considering that only gaseous and liquid SF_6 were present neglecting the existence of solid SF_6 .

3.2.1 LIQUID FLOW

Two properties, viscosity and speed of sound, characterize the difference between gas flow and liquid flow through a nozzle or an orifice. Low viscosity and low speed of sound generally enables the flow of a gas to reach sonic speeds at the constriction area of a nozzle. With liquids flowing through an orifice, due to higher viscosity of the fluid and higher speed of sound, sonic flow is rarely attainable.

Of the two properties, the speed of sound is the dominant parameter in transient flow problems and therefore it shall be briefly discussed.

SPEED OF SOUND IN A FLUID MEDIUM

The speed of sound, (a) , in a fluid medium is defined as:

$$a^2 = \left(\frac{\partial p}{\partial \rho} \right)_s$$

Where a = speed of sound
 p = pressure
 ρ = density and
 s = isentropic process (i.e. the entropy of the system remains unchanged).

Based in the above definition the speeds of sound for a gas or a liquid can be calculated and the following formulas are obtained:

For Gas

$$a = \left(\gamma_s \frac{p}{\rho} \right)^{\frac{1}{2}} = \left(\gamma_s ZRT \right)^{\frac{1}{2}}$$

Where:

$$\gamma_s = \left(\frac{\partial \ln p}{\partial \ln \rho} \right)_s = \frac{C_p}{C_v} \left(\frac{\partial \ln p}{\partial \ln \rho} \right)_T = \text{isentropic exponents. (Reference 55)}$$

$$Z = \frac{p}{\rho RT}, \text{ the compressibility of the gas}$$

R = gas constant

C_p = specific heat at constant pressure

C_v = specific heat at constant volume

T = Temperature

For an ideal gas, where $\gamma_s = C_p/C_v$ and $Z = 1$ the formula reduces to:

$$a = (\gamma_s RT)^{\frac{1}{2}}$$

In the case of a non-ideal gas such as SF₆, at high pressure and low temperature, the calculation of the speed of sound is somewhat more complicated.

Calculated values for several pressures are given in Table XX. These values have been calculated using $\gamma_s = 1.09$ (Reference 55) and value of Z obtained from Figure 57;

FIGURE 57 - COMPRESSIBILITY VS. TEMPERATURE FOR GASEOUS SF_6

TABLE XX

Speed of SF₆ at 26.7°C (80°F)

ABSOLUTE PRESSURE		Z	SPEED OF SOUND (a)	
1 x 10 ⁶ Pascals	PSIA		m/sec	ft/sec
.101	14.7	.989	135.64	445.0
1.034	150	.87	128.56	421.8
1.378	200	.82	124.85	409.6
2.067	300	.72	117.01	383.9

Liquid

In the case of a liquid the speed of sound is expressed as:

$$a = \left(\frac{\partial p}{\partial \rho} \right)_s^{\frac{1}{2}} = (\rho \beta_{ad})^{-\frac{1}{2}}$$

Where:

$$\beta_{ad} \equiv \frac{1}{\rho} \frac{\partial \rho}{\partial p} \Big|_{ad} \quad (\text{adiabatic compressibility})$$

The adiabatic compressibility is related to the isothermal compressibility (β_{iso}) and the thermal expansion coefficient α , defined as

$$\beta_{iso} \equiv \frac{1}{\rho} \frac{\partial \rho}{\partial p} \Big|_T$$

and $\alpha \equiv - \frac{1}{\rho} \frac{\partial \rho}{\partial T} \Big|_p,$

as: $\beta_{ad} = \beta_{iso} - \frac{T\alpha^2}{\rho C_p}$ (Reference 56)

β_{iso} and α for liquid SF₆ can be calculated from Figure 58.

The speed of sound for absolute pressures of 4.1 and 10.3 megapascals and at temperatures of 15°C were calculated and are shown below (Table XXI).

TABLE XXI

ABSOLUTE PRESSURE		DENSITY (ρ)		SPEED OF SOUND (a)	
1×10^6 Pascals	PSIA	kg/m ³	lbm/ft ³	m/sec	ft/sec
4.1	600	1470	91.73	188.68	947.12
10.3	1500	1559	97.34	330.07	1082.91

TRANSIENT FLOW CHARACTERISTICS IN LIQUID FLOW

In a nozzle (interrupter), that contains liquid SF₆ at high pressures, the flow fields resulting from a sudden expansion are extremely complicated. While liquid may constitute the only phase present upstream of the nozzle throat, it is likely that, for at least a short period of time, all three phases, solid, liquid and gas, may be present downstream of the nozzle throat.

The complexity of the problem then is readily appreciated, and in order to simplify the problem some assumptions are made. The results obtained are not exact and will only represent a first approximation to the solution.

The main assumptions made are that; SF₆ is an incompressible fluid, and that the flow will be sub sonic.

Under these assumptions the flow in the interrupter can be compared to a liquid flow through a sharp edged orifice valve and the flow rate can be calculated as: (Reference 57)

$$Q_o = C_d A_o \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

FIGURE 58 - PRESSURE VS. DENSITY FOR SF_6

Where Q_o = steady state flow rate
 C_d = discharge coefficient, equal to 0.63 for a sharp edged orifice.
 A_o = area of orifice's opening
 P_1 = upstream pressure
 P_2 = downstream pressure
 ρ = density of the liquid, assumed unchanged in the process. (Table XXI)

As an example the calculation for the following values is given below:

$$\begin{aligned} P_1 &= 10.335 \text{ Megapascals (1500 psi)} \\ P_2 &= 103.35 \text{ Kilopascals (15 psi)} \\ \rho &\cong 1450 \text{ kgs/cu.m. (90.5 lbm/ft}^3\text{)} \\ A_o &= 2.84 \text{ cm}^2 \text{ (.44 in}^2\text{)} \end{aligned}$$

The flow rate obtained is:

$$Q_o \cong .0213 \text{ m}^3/\text{sec (1300 in}^3/\text{sec)}$$

The corresponding average flow speed at the orifice becomes:

$$V = \frac{.0213}{2.84 \times 10^{-4}} = 75.01 \text{ m/sec (246 ft/sec)}$$

The flow rate variation of an incompressible (inelastic) liquid following a sudden valve opening has been given in Reference 57 as:

$$Q(t) = Q_o \tanh \left(\frac{t}{T_f} \right)$$

Where: $Q(t)$ = transient flow rate
 Q_o = steady state flow rate
 T_f = inertia time constant defined as follows:
 $T_f \equiv 2kT$
 $k \equiv \frac{Z_o Q_o}{2P_o}$
 $T \equiv \frac{L}{a}$, wave transmission time for a distance of L.

Where $Z = \frac{\rho a}{A}$, characteristic impedance of pipeline.
 $Q_o = A_o V_o$, volume flow rate
 P_o = reservoir pressure
 L = pipeline length
 a = sound wave velocity in the pipeline, can be assumed to be equal to the speed of sound.
 A = cross sectional area of the pipeline.
 A_o = cross section area of the reservoir
 V_o = flow speed at the exit of the reservoir.

From the flow rate equation, it can be seen that the steady state condition is practically obtained, (i.e., $\frac{Q(t)}{Q_o} = .905$), at a time $t = 1.5 T_f$.

Now T_f can be estimated for the following conditions:

$P_o = 10.335$ Megapascals; (1500 psi)
 $\rho = 1450$ Kgs/cu.m.; (90 lbm/ft³)
 $a = 305$ m/sec.; (1000 ft/sec)
 $Q_o = A_o V_o = .0213$ m³/sec; (1300 in³/sec)
 $\frac{A}{A_o} \cong .2$
 $L \cong 7.62$ cm (3 in)

The result is

$$T_f = 2(1.59)(.25) = .795 \text{ ms.}$$

The time required for establishing steady state flow is then:

$$t = 1.5 T_f = 1.5 \times .795 = 1.19 \text{ msec.}$$

The time calculated is assumed to represent the maximum time required for establishing steady state flow. It is our opinion that this time will be reduced in the presence of an electric arc since due to the arc energy a portion of the liquid SF_6 that is in the immediate neighborhood of the arc will evaporate before entering the nozzle's throat thus approximating the time delay to that for gases, which can be shown to be negligible.

3.2.2 HIGH AND LOW PRESSURE VOLUME CALCULATION

The theoretical calculations have shown that the steady flow rate through the nozzle of a liquid SF_6 interrupter can be approximated as:

$$Q_o = C_o A_o \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

It is possible to calculate the peak steady state flow rate by substituting the following values:

$$C_d = 0.63$$

$$\rho = 1570 \frac{\text{kg}}{\text{m}^3} (98 \text{ lbm/ft}^3)$$

$$P_1 = 13.09 \text{ Megapascals (1900 psi)}$$

(assuming .689 Megapascals pressure drop from the reservoir to a section just upstream of the nozzle).

$$P_2 = 310 \text{ Kilopascals (45 psi)}$$

$$A_o = 7.92 \text{ cm}^2 (1.227 \text{ in}^2)$$

The peak flow rate is:

$$Q_o = 63.75 \text{ cm}^3/\text{ms} \quad (3.89 \text{ in}^3/\text{ms})$$

By using the flow rate and the density and assuming that thermodynamic equilibrium existed the value for the minimum instantaneous mass contained in a given HP volume at a given minimum pressure can be calculated. Again by using the conditions given by a minimum instantaneous pressure, the minimum steady state flow rate is calculated thus determining the upper and lower limits of flow.

Establishing as a design objective that the pressure drop at the end of 1 ms of arcing is not to exceed 20% of the initial pressure and at the end of 8 ms a minimum pressure of 2.1 Megapascals (300 psi) still exists it is possible to calculate the approximate volumes required. A tabulation of this calculation is given in Table XXII.

From the calculated values it is observed that a volume of 3.28 liters (200 cu. in) can fulfill the design objectives for a high pressure volume reservoir.

The design objective for the low pressure (LP) volume is to provide sufficient capacity for relieving the pressure build up caused by the flow of mass so that the flow rate at the nozzle is not substantially altered. This condition is especially critical at the end of 8 ms of flow, which represents the arbitrarily selected maximum arcing time.

Assuming an initial downstream pressure of .3 Megapascals (45 psi) and a total mass flow of .8 kg (Table XXII) the LP volume required to ensure sonic speed flow at the nozzle's throat (i.e. in a gas, the downstream pressure is not higher than half of the upstream pressure) was calculated to be 16.7 liters (1017 cu. in).

TABLE XXII

FLOW RATE AND PRESSURE CALCULATION*

P₁ (initial) 13.78 Megapascals T = 21°C

HIGH PRESSURE VOLUME		INITIAL SF ₆ MASS		Min. Pressure @ 1 ms		Min. Flow Rate @ 1 ms, % of Peak	Min. Pressure @ 8 ms		Max. Total Mass Flow for 8 ms		Min. % of Liquid After 8 ms Flow
Liter	Cu. In	kg	Lbm	MPa	Psi		MPa	Psi	kg	Lbm	
5.96	364	9.1	20.06	12.4	1800	94.8	4.13	600	.8	1.76	100
4.10	250	6.44	14.2	11.8	1709	92.4	2.05	298	.8	1.76	100
3.28	200	5.17	11.4	11.3	1636	90.5	2.05	298	.8	1.76	95
2.46	150	3.86	8.5	10.4	1515	87.0	2.05	298	.8	1.76	88

*Assume thermodynamic equilibrium existed.

3.2.3 INTERRUPTER

The new interrupter design basically represents an enlargement of the 19mm nozzle diameter model previously tested. The new design is shown in Figure 59. A description and design justification for the moving contact and the shock absorber follows.

MOVING CONTACT

The primary considerations given to the design of the moving contacts are not directly related to the interrupting function but rather to the mechanical aspects dictating the opening characteristics of the interrupter.

In this design, (Figure 60), as in the previous ones, the interrupting contact is used as a piston where the pneumatic force produced by the upstream pressure acts as the accelerating force for opening the contacts. It is therefore essential that proper dimensioning of the piston area be carefully examined. It is also important that as the contact is enlarged in diameter its total mass is not greatly increased.

As before, it is required that this contact be disengaged, (time to contact part), 1 ms after the trip signal is given, and that its maximum gap of 25mm be attained in a time of 1 ms, or less.

To maintain the contact in the closed position a latching force of approximately 4450 Newtons (1000 lbs) is exerted on the piston's, (moving contact), differential area by the high pressure SF_6 .

When the high pressure seal is broken, during a tripping operation, an effective area of 49.7 sq. cm. is exposed to the high pressure. Assuming that during the first millisecond, after the opening of the valve, the pressure has dropped to 10.3 megapascals (1500 psi) and also assuming a friction force of 1340 Newtons (300 lbs), the net accelerating force becomes:

$$F = 50 \text{ Kilonewtons (11250 lbs)}$$

FIGURE 59 - LIQUID SF₆ INTERRUPTER

FIGURE 60 - MOVING CONTACT FROM
LIQUID
SF₆ INTERRUPTER

FIGURE 61 - BUMPER ASSEMBLY FROM LIQUID SF₆ INTERRUPTER

Using this value for the force and knowing the mass of the contact (1.5 kg) the travel of the moving contact for an assumed constant acceleration can be calculated (Table XXIII).

TABLE XXIII
TRAVEL OF MOVING CONTACT
F = 50 Kilonewtons; M = 1.5 Kilograms

Contact Travel	mm	0	1.6	6.4	31.8
	in	0	0.063	0.25	1.25
Time	ms	0	0.3	0.834	1.648
EVENT	Energizing Impulse Coil	Seal Breaks Acceleration by Pneumatic Force Begins	Contacts Part Arcing Begins	End of Stroke Arc Interrupting	

BUMPER STOP

At the end of its stroke the moving contact is traveling at a velocity of approximately 47.25 meters per second (105 miles/hr), and its Kinetic energy is approximately 1532 joules (1130 ft-lbs).

To absorb this energy and to stop the contact's motion in a reasonably short distance becomes a difficult task. The need for a short stopping distance is emphasized because it relates directly to the mass of the moving contact. A larger stopping distance signifies a longer and therefore heavier moving contact.

Two concepts of a damping system that can be used for absorbing the kinetic energy have been considered.

The first system considered the possibility of using rubber as the energy absorbing medium. The second system contemplates the use of a hydraulic medium which is inherently available with the presence of liquid SF₆.

The later system was not adopted since space limitations in the interrupter design prevented the proper metering of the liquid that would be necessary for control of the pressure build-up, which can be significant due to the low compressibility of liquid SF_6 .

The rubber damping system was adopted in the design and is shown in Figure 61. In this design two rubber rings are employed. One is located in the upper end of a floating cylinder and just underneath of the moving contact. The floating cylinder, as is implied, is an unfastened member having a mass approximately equal to the mass of the moving contact. When impact between the upper rubber and the contact occurs, the pneumatic force acting upon the contact will support the forward motion of both the floating cylinder and the moving contact. The combined mass then will move at approximately one half the original speed thus reducing the kinetic energy in the contact to one half. The remaining half of the original kinetic energy plus the additional energy acquired during the damping process will be absorbed by the second larger rubber ring which is located at the bottom end of the floating piston.

3.3 INTERRUPTER PERFORMANCE

The performance of the interrupter is evaluated according with the results obtained in a series of tests consisting of:

- A. Mechanical
- B. Continuous current carrying
- C. Momentary current
- D. Current interrupting
- E. Dielectric

MECHANICAL TESTS

This was an abbreviated series of operational test directed primarily to detect areas of potential mechanical problems and to observe the opening speeds that could be obtained under normal operating conditions.

Special attention was given, during these tests, to the blast valve (moving contact) seal. Originally this seal was a molded rubber ring vulcanized into an adapter plate.

When using this seal assembly it was observed that as the reservoir pressures were increased beyond a certain point a large leak developed which caused the contact to open. The cause for the improper operation was traced to the rubber characteristics. These strain vs stress characteristics of the rubber are plotted in Figure 62. Data for the construction of these curves was obtained under static conditions.

At the working pressure of 13.8 megapascals (2000 psi) the compressive strain diagram shows a flattening out at a value of approximately 0.29. Since the rubber seal is 3.35mm thick, the deflection of the rubber in the pressure region would then be approximately 2.3mm. The maximum penetration of the sealing edge of the moving contact is 1.57mm, any additional penetration would signify that the flat top surface of the contact comes in direct contact with the rubber surface thus substantially increasing the compression area from 4.64 cm² to 12.39 cm². This suggests that either the sealing edge of the contact should have an increased penetration at least equal to the high pressure deflection of the seal, 2.3mm, or a latching pressure applied to the underside of the contact must be increased to 3.6 megapascals (523 psi) to effectively seal the operating pressure of 13.78 megapascals.

Both of these solutions were deemed unacceptable and an alternate seal design was chosen. This design consists of a standard "O" ring trapped in an open groove (Figure 63). It proved to be a satisfactory solution to the problem and was adopted as part of the final design.

Another problem found in these tests was the design of the stationary contact fingers. It was apparent that each individual copper finger had become annealed when the arc resistant (Cu-W) material was brazed on. Due to the high forces created by the pressure blast acting on the face of these fingers some bending was observed.

To avoid this condition it is suggested that the finger design be re-evaluated and that the possibility of eliminating individual contact fingers be explored.

FIGURE 62 - COMPRESSIVE STRESS - STRAIN DIAGRAMS FOR RUBBER PARTS USED IN HP SYNCHRONOUS TRANSMISSION INTERRUPTER

FIGURE 63 - LIQUID SF₆ INTERRUPTER USING "O" RING SEAL

The measurement of the opening velocity was made with the aid of a high speed motion picture (4500 to 6500 frames per sec.). The contact parting time was measured with an oscilloscope.

The data obtained during these measurements is presented in Table XXIV and the results of tests, made with identical back pressures (1.4 megapascals (200 psi)) and approximately equal coil energy input, are plotted as a function of the high pressure in Figure 64.

FIGURE 64 - CONTACT PARTING MEASUREMENTS

TABULATION OF DATA - TABLE NO. XXIV

CONTACT PARTING MEASUREMENTS

Impulse Coil Input μf , Volts	H.P. Pressure 1×10^6 Pascals	Back Pressure 1×10^6 Pascals	Contact Parting Time ms	Time Req'd For 25mm Contact Gap ms
192 , 2400	13.1	1.4	1.60	-
192 , 2450	12.4	1.2	1.50	-
288 , 2200	13.8	.7	1.25	-
288 , 2200	13.8	.7	1.68	-
288 , 2200	13.5	.7	1.70	-
288 , 2200	13	.7	1.71	-
288 , 2200	12.4	.7	1.65	-
288 , 2300	13.8	1.4	1.36	0.85
288 , 2300	13.8	1.4	1.50	0.85
288 , 2400	~ 2.1	$\sim .2$	1.41	-
288 , 2400	13.6	.7	-	0.89
288 , 2400	12.1	.7	1.58	-
288 , 2400	13.8	~ 1.0	1.30	-
288 , 2400	13.8	1.4	1.40	0.92
288 , 2400	12.4	1.4	1.53	0.88
288 , 2400	12.4	1.4	1.49	-
288 , 2400	12.4	1.4	1.60	-
288 , 2400	11.7	1.4	1.60	-

From the results obtained it is evident that the operating times originally specified are not out of reach and may easily be attained by increasing the energy input to the repulsion coil.

CONTINUOUS CURRENT CARRYING TESTS

These tests were conducted to determine the temperature rise, above the ambient, of the interrupter parts when carrying continuously a current of 3000 amperes RMS.

In addition to determining the temperature rise, measurements were made of the contact resistance. These results then were correlated to the temperature readings in an attempt to establish the temperature vs contact resistance relationship for the tested model.

The total number of main contact segments used in those tests was 30. Each segment had a contact force of 62 Newtons (14 lbs). The fingers, or segments, as it is shown on Figure 59 had a relatively small engagement with the moving contact (5mm). The contact penetration was kept small in order to minimize the contact travel, thus reducing the opening time, and at the same time maintaining the required time overlap between the parting of the main contacts and the parting of the arcing contacts.

It was of special interest to observe the behavior of the moving contact, where high strength aluminum was used as the current carrying material. The aluminum contact, when compared to a similar copper contact, has four times higher resistance and has about one third of the thermal conductivity.

The temperature measurements were made using thermocouples mounted in the locations shown in Figure 65. Before the initiation of each test the resistance across the interrupter was measured. Heat run tests were performed at resistance readings of 257, 200, 73, 42.5 and 39.5 micro-ohms. The changes in resistance generally resulted from slight increases in the main contact penetration and careful realignment of the contacts. The highest resistance point was determined to be the interface between the main contacts and the moving contacts. Resistance measurements made along the current path revealed that even when the total resistance had been reduced to 40 $\mu\Omega$ approximately 75% of it was across the main contacts interface.

FIGURE 65 - TEST MODEL - THERMOCOUPLE LOCATION AND STEADY STATE TEMPERATURE RISE

The test series performed when the resistance was 42.5 $\mu\Omega$ is considered to provide typical results and they are tabulated in Table XXV. From these results it is seen that the hot spot corresponded to the arcing contact where a maximum temperature rise of 83°C was observed. This point was selected to plot a curve showing the effects of the interrupter resistance upon the hot spot temperature rise. This plot is shown as Figure 66. It is possible from this graph to obtain a relationship between the resistance of the interrupter and the temperature rise of the hot spot. This relationship can be expressed as:

$$T(^{\circ}\text{C}) \propto [R(\mu\Omega)]^{.2}$$

It is evident from the results that steps must be taken to reduce the resistance across the interrupter. A reduction, to approximately 13 $\mu\Omega$, should result in a maximum temperature rise of 65°C. If the reduction of the resistance can not by itself reduce the temperature rise to an acceptable limit, it will be necessary to use a material having a higher thermal conductivity, or to provide a larger conductive cross sectional area.

The reduction of the contact resistance can also be accomplished by increasing the number of contact fingers.

MOMENTARY CURRENT TESTS

These tests were performed in accordance with standard test procedures used for power circuit breakers. At the initiation of each test the resistance across the device was measured and recorded. The current was increased in steps of approximately 20kA RMS up to the required test values as tabulated in Table XXVI.

The interrupter passed all these tests successfully. No noticeable change in resistance across the device was observed after the first test, thus indicating that the contact surfaces were not damaged. This was later confirmed upon disassemble of the interrupter.

FIGURE 66 - EFFECTS OF RESISTANCE UPON PEAK TEMPERATURE RISES, (3000 AMP, RMS CURRENT)

TABULATION OF DATA - TABLE NO. XXV

Temperature Rise Above Ambient (°C) - 3000 Amp. RMS

Location No.	Time Elapsed, Hours										
	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	6.5	7.0
1	29	46	57	64	68	71	72	73	77	77	77
2	33	49	61	68	72	74	76	78	82	82	82
3	37	52	63	69	74	76	77	79	83	83	83
4	31	48	59	66	70	72	74	75	79	79	79
5	36	50	60	67	70	72	73	74	77	78	77
6	33	48	58	65	69	71	72	73	76	77	77
7	37	51	61	68	72	74	75	76	80	80	81
8	23	33	42	48	52	54	56	58	62	62	63
9	21	31	39	45	49	52	53	55	59	59	60
10	13	21	29	35	39	42	44	46	49	50	50
11	6	13	19	25	29	31	33	35	38	39	39
12	0	1	1	1	1	1	1	4	3	1	2
13	-	-	-	-	-	-	-	-	-	-	-
14	3	8	13	17	20	22	24	26	29	29	30
T(amb.)	30	30	30	30	30	30	31	31	29	28	27

TABULATION OF DATA - TABLE NO. XXVI

MOMENTARY CURRENT TEST

Test No. & Date	Current Through Device (1)				Duration of Current Flow, ms	Resistance Measured Before each Test $\mu\Omega$
	Total Current kA, RMS	Alter. Component kA, RMS	Peak Current kA	I_t/I_a (2)		
5/19						
1	30.5	22.2	52.3	1.37	160	53
2	70.7	52.7	121.6	1.34	162	30
3	99.5	75.9	171.7	1.31	171	31
5/20						
4	135.9	102.1	234.1	1.33	171	34
5	-	103.0 (Sym. Current)		-	1023	31

NOTE: (1) Measured at first current zero after current initiation.

(2) Ratio of total current to the alternating component current.

INTERRUPTING TESTS

As it may be recalled, a maximum dv/dt of approximately $4\text{kV}/\mu\text{s}$ was obtained at a di/dt of $48\text{ Amps}/\mu\text{s}$, using a 19mm nozzle diameter and 10.34 megapascals of upstream pressure. Based upon this performance it was predicted that by increasing the nozzle diameter to 31.75mm and the pressure to 13.78 megapascals the dv/dt could be increased to approximately $18\text{kV}/\mu\text{s}$.

To demonstrate this assumed performance, interrupting tests were conducted using the new interrupter design. The method of testing was in all respects similar to the method previously used. That is the direct synthetic, or capacitor discharge test method described earlier in this report.

One of the problems, found earlier with this interrupter was related to the strength of the contact fingers. In order not to exceed the elastic limit of the finger material it was found necessary to perform the test at 8.3 megapascals (1200 psi). Using the 1.5 power relationship between pressure and dv/dt it is expected that operating at the lower pressure the dv/dt capability would be reduced to $8.4\text{kV}/\mu\text{s}$.

The initial results obtained with the interrupter indicated that an excessive pressure drop occurred prior to the point of interruption suggesting that a larger volume of liquid SF_6 may be required in order to reduce the drop in pressure.

The interrupter design was reviewed and the upstream volume was increased from the original 3 liters (182 cu.in) to 3.67 liters (224 cu.in). This represents a total increase of 24% .

Prior to the increase of the upstream volume the performance of the interrupter was rather poor. At a di/dt of $45\text{ Amps}/\mu\text{s}$ a maximum dv/dt of only $1.3\text{kV}/\mu\text{s}$ was obtained, and at a di/dt of $28\text{ A}/\mu\text{s}$ the corresponding dv/dt was $5.2\text{kV}/\mu\text{s}$.

After increasing the volume the tests were resumed and a very slight increase in performance was observed. The increase in the HP volume caused the pressure to decrease at a slower rate and helped to reduce the magnitude of the pressure oscillations recorded in previous tests. However, at this

time it was found that the flow area of the orifices connecting the two chambers of the HP volume was not sufficiently large to ensure that a constriction, and therefore a drop of pressure, was not taking place in this connecting region. The orifices which are located in the support structure for the moving and transfer contacts (Figure 59) were then enlarged and the tests were initiated once more.

The pressure traces obtained demonstrated that the flow had indeed been restricted at these parts. The pressure drop under this condition showed a much faster decline in pressure which is understandable since the pressure transducer is located in the lower chamber.

The test data obtained under these conditions has been tabulated and is shown in Table XXVII.

The results, as it can be seen, are quite short of the expected performance for this interrupter. The tests indicate that with a di/dt of $48 \text{ A}/\mu\text{s}$ a dv/dt of $3.6 \text{ kV}/\mu\text{s}$ was obtained. At $40 \text{ A}/\mu\text{s}$ a dv/dt of $5.5 \text{ kV}/\mu\text{s}$ was observed. By extrapolating these results and comparing them with the predicted values, as well as with the recovery voltage levels obtained earlier with the smaller nozzle, it can be concluded that the present interrupter is not performing at its optimum level. The cause for this inefficient performance is not fully understood at this time, but it is suspected that it is related to two conditions observed in the tests records (Figure 67 and 68):

1. An excessive pressure drop taking place during the time the contacts are just beginning to open. From the test data it was observed that the pressure may have been as low as 4.1 megapascals (600 psi) at the current zero, and
2. An extreme sensitivity to the arcing time. It was observed that in order to obtain a good interruption the arcing time had to be greater than 1.3 ms but less than 1.45 ms. Arcing times outside of these limits resulted in failures to interrupt.

TABULATION OF DATA - TABLE NO. XXVII

SYNCHRONOUS TRANSMISSION BREAKER

PASS OR FAIL	E _o kV	di/dt A/μs	HP PRESS. 1 x 10 ⁶ PASCALS	ARC TIME ms	de/dt CAL. kV/μs	de/dt MEAS. kV/μs	L _s μh	R _a Ω
FAIL	16	45	8.27	1.1	4.1	1.8	250	100
PASS	22	35	8.27	1.4	4.7	-	500	150
FAIL	22	33.7	8.27	.95	4.7	4.02	500	150
FAIL	17	40	8.27	1.3	5.4	-	250	150
PASS	17	38	8.27	1.45	5.4	10.5	-	-
FAIL	21.5	46.2	8.27	1.55	4.3	-	250	100
FAIL	21.5	48	8.27	1.62	1.4	-	250	25
FAIL	21.5	48	8.27	1.5	1.0	-	250	14
FAIL	21.5	48	8.27	1.4	.8	.46	250	10
PASS	21.5	46.8	8.27	1.4	1.0	.86	250	25
PASS	21.5	47.8	8.27	1.45	2.4	1.65	250	50
FAIL	21.5	45.7	8.27	1.5	3.3	-	250	75
PASS	21.5	45	8.27	1.4	3.3	-	250	75
FAIL	21.5	45.2	8.27	1.35	4.3	-	250	100
FAIL	21.5	47.8	8.27	1.3	3.4	2.5	250	75
PASS	21.5	48.1	8.27	1.4	3.4	2.5	250	75
FAIL	21.5	45.7	8.27	1.45	4.2	-	250	100
PASS	18	39.7	8.27	1.4	7.1	6.4	250	200
FAIL	18	38.7	8.27	1.4	8.8	8.0	250	250
FAIL	18	37.5	8.27	1.4	7.1	6.4	250	200
FAIL	18	39.8	8.27	1.25	7.1	-	250	200
PASS	18	40.8	8.27	1.4	5.4	3.2	250	150
FAIL	21.5	46.7	8.27	1.35	3.8	3.2	250	85
FAIL	21.5	48.8	8.27	1.4	3.6	2.3	250	75
PASS	21.5	48.2	8.27	1.3	3.6	2.5	250	75
PASS	21.5	47.8	8.27	1.3	3.8	2.55	250	85
FAIL	21.5	45.7	8.27	1.35	4.4	2.5	250	100
FAIL	21.5	48 Cal	8.27	1.3	4.4	-	250	100

FIGURE 67 - INTERRUPTING TEST 8.27×10^6 PASCALS SF_6

$P = 3.45 \text{ MPa/DIV}$
 $I = 8160 \text{ A/DIV}$
 $E(\text{ARC}) = 968 \text{ V/DIV}$
 $T = 1 \text{ ms/DIV}$

FIGURE 68 - INTERRUPTING TEST 8.27×10^6 PASCALS SF_6

$I = 1020 \text{ A/DIV}$
 $E(\text{TRV}) = 7.17 \text{ kV/DIV}$
 $T = 10 \mu\text{s/DIV}$

The most likely cause for the rapid decrease in pressure appears to be one of the simplifying assumptions made in the calculations of the high pressure volume. That is the decision to neglect the effects of the volume expansion produced by the motion of the moving contact. A re-evaluation of the changes of volume reveals that since the compressibility of the liquid SF_6 is in the order of $7.25 \times 10^{-9} \text{ pascals}^{-1}$ ($5 \times 10^{-5} \text{ psi}^{-1}$) it is possible to expect a change of 1.38 megapascals (200 psi) for a 1% change in density. Translating these values to the contact motion it can be shown that:

1. At the time of contact part a pressure drop of 1.28 megapascals (185 psi) can take place and
2. At the end of the contact's stroke the total drop in pressure can be as much as 6.86 megapascals. (995 psi).

It does not appear likely that other assumptions made regarding to the mass flow and the thermodynamic processes would produce errors that will justify the magnitudes of the pressure drop observed. Nevertheless, it is highly advisable that the basic flow characteristics of liquid SF_6 be studied in detail. A better understanding of the dynamics of the liquid SF_6 may possibly provide the answers for the pressure oscillations recorded and may even provide some clues as to the observed criticality of the arcing times.

Inspection of the interrupter parts after the tests were concluded revealed an excellent burning pattern and a good control of the arc. The contact erosion was very minimal (Figures 69 and 70). Some burning, indicating that the arc had been terminated along the diverging angle of the stationary arcing fingers, was observed (Figure 71). This pattern is an indication that the arc had indeed shortened itself after having transferred. This peculiar behavior is another area that should be investigated to determine if there is a definite connection between the possible changes in arc length and the pressure oscillations that have been recorded.

FIGURE 69 - STATIONARY CONTACT
LIQUID SF_6 INTERRUPTER

FIGURE 70 - MOVING CONTACT
LIQUID SF_6 INTERRUPTER

FIGURE 71 - STATIONARY CONTACT FINGERS
LIQUID SF₆ INTERRUPTER

NON SYNCHRONOUS INTERRUPTION

Although no formal and extensive testing was done to establish the non-synchronous capability of the interrupter, several interruption tests were made at a current level of 40kA rms, and a driving voltage of 8kV rms.

The interrupter was operated at a reduced pressure of 1.9 megapascals (280 psi). The total arcing time was approximately 9 ms.

The interrupter successfully interrupted the current and no appreciable deterioration of the contacts was observed. The primary objective of these tests was to demonstrate that at this reduced current level the interrupter will not be damaged by a non-synchronous operation. It is believed that higher driving voltages can be successfully withstood by the interrupter even at the reduced pressure levels. Tests designed to demonstrate the maximum non-synchronous capability of the interrupter should be considered in the

future. However, before any of these tests are pursued the excessive pressure drop problem must be solved in order to enable the interrupter to maintain an adequate mass flow for the appropriate length of time dictated by the maximum arcing time expected of the interrupter. Initially this arcing time requirement has been set at 8 ms.

DIELECTRIC TESTS

Concurrently with the non-synchronous interrupting tests, the impulse withstand capability of the interrupter at reduced pressures was investigated and the following results were obtained:

0.9 Megapascals (130 psi) $\approx$ 450kV Crest

1.45 Megapascals (210 psi) $\approx$ 560kV Crest

Since it has been reported that no discontinuities have been observed in the impulse breakdown voltage in passing from the gas to the liquid phase (Reference 58) it is possible to assume that at the full operating pressure the impulse withstand will be proportionally increased. It is therefore safe to assume that the 650kV BIL rating for a 145kV interrupter can be easily achieved with the present design. This withstand capability is well beyond the original requirements for the interrupter. As it may be recalled, the function of dielectric isolation was assigned to the series isolating break proposed as an integral part of the breaker design.

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APPENDIX I

WESTINGHOUSE ELECTRIC CORPORATION

ELECTRONIC TUBE DIVISION

ELMIRA, NEW YORK

VACUUM INTERRUPTER APPLICATION NOTE #4

WESTINGHOUSE CLR CONTACT MATERIAL

Westinghouse has introduced in its vacuum interrupters a new, high-current-interrupting material, called CLR, that is superior to the copper alloy material commonly used for high-current interruption. Among its advantages are lower chopping current, higher voltage capability, and lower erosion, details of which are described below.

Chopping Current

(TM) CLR	1 - 4 amp	median 2.7
Copper alloy	3 - 15 amp	median 7.0

Chopping current causes high surge voltages which are proportional to the magnitude of the chopping current and which may be high enough to puncture insulation unless additional protection - such as lightning arrestors or capacitors - is used in the circuit. The value of chopping current of CLR is less than that of oil breakers, while the copper-bismuth chopping current is higher.

Prestrike Distance on Closing

(TM) CLR	.006"	at 15 kV rms
Copper alloy	.060"	at 15 kV rms

As the contacts of the vacuum interrupter approach one another, the gap will break down at a point called the prestrike distance. The amount of erosion and possible circuit disturbance are a function of this distance.

Erosion

(TM) CLR - 1/3 Copper alloy

Long life tests comparing CLR and copper alloy show that the life of CLR is more than three times that of copper alloy.

On high-current interruption, local erosion is so severe in copper alloy tubes that jets of copper are splattered throughout the vacuum interrupter; but in CLR tubes the erosion of the contact is relatively quiet and the material smoothly coats the elements of the vacuum interrupter.

High Voltage BIL

(TM) CLR	-	Maintains
Copper alloy	-	Degrades

Tests show that when the vacuum interrupters with copper alloy interrupt either normal or short-circuit currents, the BIL voltages degrades, but with CLR this does not happen.

Shorter Contact Stroke

Because vacuum interrupters with CLR maintain their high-voltage withstand characteristic better than vacuum interrupters with copper alloy after arcing, the 1200 amp vacuum interrupter with CLR can be operated at a 0.5" contact stroke length compared to competitions' 0.75" length.

Strength

(TM) CLR	-	Does not distort
Copper alloy	-	Spirals move under certain impact

Under certain conditions of closing impact, the copper spirals of the contacts used in high-current vacuum interrupters move and are distorted, but with CLR under the same conditions, this did not happen.

In respect to weld strength, however, CLR has a contact weld strength that is about 7 times that of the copper-alloy material. The welds can be broken with reasonable impact energy from the wipe spring if the spring is placed close to the vacuum interrupter and if the mounting for the vacuum interrupter is made as stiff as is practical.

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