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**Technical Feasibility Study of Railroad
Electrification with High Voltage
(10-50 kV) Direct Current**

Carnegie-Mellon Univ, Pittsburgh, Pa Transportation Res. Inst.

Prepared for

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16. Abstract High-voltage (10-50 kV), direct-current (HVDC) power distribution may prove to be an economically and technically attractive option for railroad electrification. There may be potential economic advantages in both wayside installation and operation, and in the propulsion equipment aboard the rolling stock. However, before an economic comparison with AC systems can be completed, the technical feasibility of DC systems must be determined, which was the purpose of this study. This study was directed toward the wayside equipment only. The problem of HVDC rolling stock was not considered. The preliminary analysis in this report shows no technical obstacle to the use of HVDC power distribution systems for application to the wayside portion of railroad electrification. Circuit breakers, which can be applied to these systems, are in various stages of development, and with reasonably directed research can meet the duty requirements. Likewise, rectifiers which can satisfy both current and voltage requirements are within the state of the art. An alternate to using the DC breaker (namely, sectionalizing on the AC side of the system) is a viable option. This option can sacrifice some operational flexibility as well as performance.			
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1.0 INTRODUCTION

1.1 BACKGROUND

Research⁽¹⁻²⁾ performed for the Department of Transportation (DOT) concluded that High Voltage Direct Current (HVDC) power distribution for high speed ground transportation may prove economically attractive if the circuit breakers which can handle both the voltage and current involved can be developed at reasonable cost. Research which led to this conclusion was performed in 1969. Since that time, circuit breaker technology in the area of extra high voltage DC transmission⁽³⁻⁴⁾ has advanced rapidly.

The present efforts of the Federal Railroad Administration (FRA) are directed toward electrification of the high speed test loop at the Transportation Test Center at Pueblo, Colorado, electrification of the Northeast Corridor and studies of the feasibility of electrification of railroad properties. This latter effort is concerned with cost, economic and environment impact and electrification options. The present study is a contribution to electrification options and provides FRA with an initial technical analysis of HVDC (10-50kV) electrification of railroads.

There may be potential economic advantages in both wayside installations and rolling stock of railroads electrified with HVDC. Even though each rectifier substation will cost more than the AC substation, total cost for all substations for the HVDC installation could be less than that of the AC installation. Likewise, propulsion equipment aboard the rolling stock may have some cost and weight advantages in the long run. However, before such cost analysis can be completed, the technical feasibility must be determined. This determination is the purpose of the present study.

1.2 SCOPE OF WORK

This study had three principal objectives:

1. A review of the state-of-the-art for HVDC distribution system components with particular emphasis on circuit breaker development and rectifier practice,
2. A survey of experience on lower voltage D.C. power distribution systems, evaluation of the problems encountered, and a projection of the results to HVDC systems,
3. Investigation of alternatives to the DC breaker including sectionalizing on the AC side of the system and using series pole connections of three phase AC circuit breakers for the HVDC circuit breaker.

Areas for further research efforts are also identified.

1.3 ORGANIZATION OF REPORT

Section 3.0 of this report contains a discussion of the system aspects of railroad electrification. These must be considered in any meaningful consideration of electrification components.

Section 4.0 has a description of the potential types of HVDC switch gear for application including those based on solid state, metal plasma, gas plasma and more conventional devices. A qualitative comparison among the various concepts is made and some of the concepts are prioritized for further development work.

Section 5.0 contains a discussion of rectifier practice and components which may be applied to HVDC railroad electrification, and Section 6.0 has a review of operating experience and practices which are projected to HVDC systems.

Recommendations for future research as well as a step-by-step plan for achieving this research is covered in Section 7.0. A bibliography is included in Section 8.0.

2.0 SUMMARY

2.1 CONCLUSIONS

This preliminary analysis shows no technical obstacle to the development of HVDC power distribution systems for application to railroad electrification.

1. Circuit breakers, which can be applied to HVDC power distribution, are in various stages of development and with reasonable, directed development effort, could be applied for railroad use.

2. Rectifiers are now available which can satisfy the load and voltage requirements posed by HVDC railroads. Although prototype installations should be tested before any practical employment, not much development work is necessary.

3. The alternative to the DC breaker, namely sectionalizing on the AC side of a HVDC power distribution system is a viable option with the sacrifice of some operating flexibility.

4. Any HVDC power distribution system for railroads must be designed as a total system. Circuit breakers, relay/interlock subsystems, distribution aspects (catenary, back up distribution cables etc.), and lightning protection must be considered at the beginning of the design analysis.

2.2 Recommendations for Future Research

The results of this study indicate that there are five steps which will take the effort of HVDC railroad electrification from the feasibility stage to a prototype demonstration. The last two steps are conditional and will depend primarily on the outcome of step 3.

1. All parameters necessary to specify a complete HVDC distribution system for railroads should be identified and their ranges determined where applicable. This specification should be determined knowing the parameters of the comparable AC distribution systems and keeping them in the forefront.

2. A study of the five most viable candidates for use as DC circuit breakers which include the force-commutated vacuum interrupter, the magnetically actuated vacuum interrupter, the force commutated liquid metal plasma valve, and modification and application of a present magnetic-air breaker should then be undertaken using the system parameters generated in Step 1. The outputs of the study should be principally economic and should include estimates of development costs, production prices per unit and operating and maintenance costs. An economic and technical study of the alternative to the DC breaker, namely, switching and protection on the AC side of the power distribution system, should be completed.

3. A comparison of high voltage AC vs DC power distribution should be completed at this stage. Both motive power aboard vehicle and wayside installations should be considered in terms of total life cycle cost. If the result of this study indicate that HVDC distribution is economically sound, (perhaps 10-25% less costly than AC) then risks and rewards of DC electrification would be considered and a decision to proceed through the next two steps should be made at this time.

4. Based on the outcome of Step 2 and 3, candidates for circuit breaker development could be selected for design, fabrication and laboratory testing.

5. If DC distribution system economics and technical performance prove viable, a small prototype demonstration should be undertaken.

Step 4 would only be completed if a decision were made to use DC electrification and to use the DC breaker rather than switching on the AC side.

3.0 POWER DISTRIBUTION SYSTEM CONSIDERATIONS

Within the external constraints such as compatibility with other railroads or commercial availability of electrification equipment, the choice of the power distribution system for electrification is generally based on economics. There have been several studies^(1,5-8) on the economic and technical considerations involved in the selection of AC or DC electrification for railroads and rapid transit systems.

There are many factors which influence the capital and operating cost of electrification. Both wayside and rolling stock equipment must be considered in any tradeoff analysis. The answers are generally sensitive to the kind of operation desired by the railroad. Thus, to determine the answer of AC vs DC electrification, the operational characteristics and technical performance requirements must first be determined.

3.1 COMPARISON OF HVDC DISTRIBUTION SYSTEMS

Several configurations of DC power distribution systems have been applied to electrified railroads and rapid transit systems. Normally, at low voltage DC (600-3000V), a banked secondary network is used in which adjacent substations feed the load through one or several trolleys on a many parallel-track railroad. Isolation of trolley segments, fault protection of the system and power switching functions are provided by DC breakers.

A typical substation arrangement for a two parallel track railroad is shown in Figure 1. In this DC distribution system, flexibility is obtained by:

1. A capability to operate through any transformer-rectifier unit.
2. A capability to have the tie breaker normally open or normally closed.

In the latter position, adjacent substations are banked through both trolleys allowing better voltage regulation for the load.

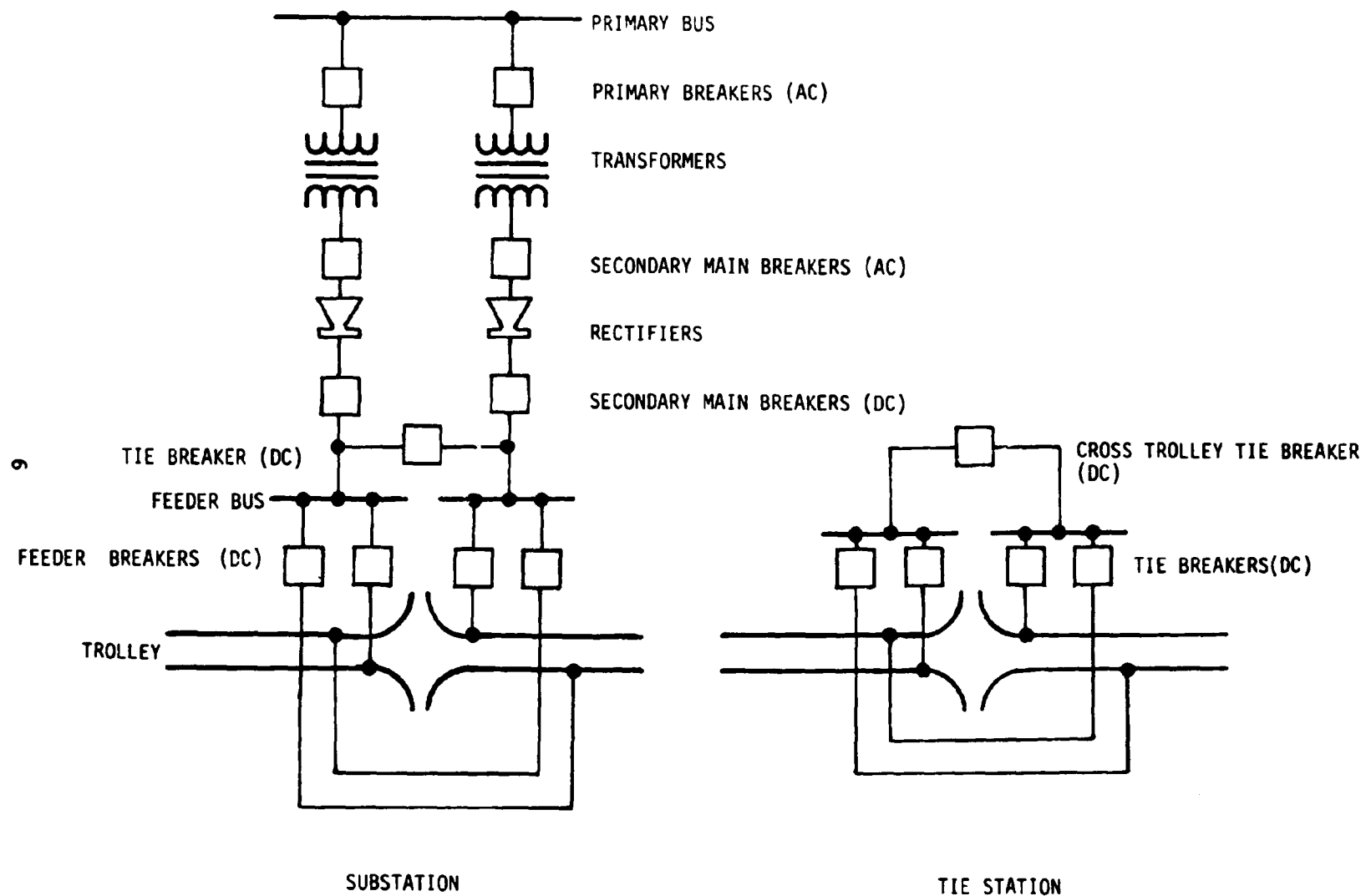


Figure 1 DC Substation and Tie Station Using DC Breakers for Isolation, Protection and Switching.

Tie stations are also used in the bank secondary network. An example of a tie station is shown in Figure 1. Tie stations contribute to system flexibility by providing isolation capability in the event of a fault and provide better voltage regulation.

Both substations and tie stations using DC breakers could also be used for HVDC distribution for railroads in a similar system configuration.

A second general class of DC distribution systems are those which use AC breakers for fault protection and motor driven disconnect switches for isolation and switching. One such system configuration is shown in Figure 2. The disconnect switches are never operated under load. The AC breakers are used to cut all power and then the disconnect switches are operated.

The feeder disconnects of Figure 2 feed both tracks and the adjacent substation also feeds both tracks. If a fault occurs in this section, the secondary main breaker (AC) opens in both substations, the appropriate disconnect switches open and the AC breaker restrikes establishing power. Each track section can be fed from either transformer in the event of maintenance on the substation.

Tie stations consisting of disconnect switches rather than the DC breakers of Figure 1 can be employed. Fault detection capability should be provided at the tie station.

DC distribution systems which depend on AC breakers and disconnect switches may require more extensive fault detection and relay/interlock logic than those using DC breakers. Fault clearance times may be slightly longer and will be determined by the operation time for the motor driven switches. However, these clearance times are not expected to be excessive. There is no known technical impediment to implementing such a power distribution system. Thus, the DC distribution system which depends on AC breakers for fault protection and motor driven disconnect switches for isolation and switching is a viable alternative

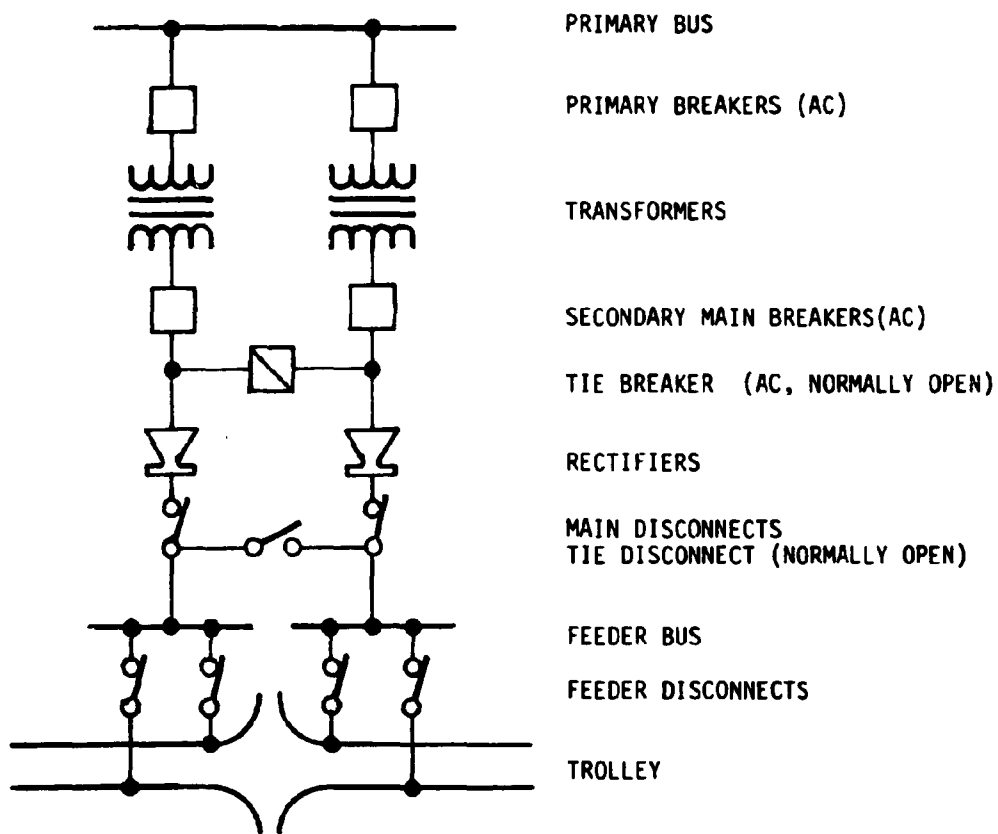


Figure 2 DC Substation Using AC Breakers for Protection and Disconnect Switches for Isolation and Switching.

for high voltage application. This alternative warrants more attention because HVDC breakers are expected to be expensive.

3.2 DESIGN CONSIDERATIONS

Specification of electrification equipment for HVDC railroads is a system engineering job. Fault protection, isolation and switching requirements should be considered at the beginning of the job and not at the end. In some cases, fault protection may significantly influence the system cost.

Several parameters are required to specify a HVDC distribution system.

Some of the more important are:

1. System Voltage (Maximum, nominal, minimum)
2. System Loads (Maximum, nominal, minimum)
3. Substation Spacing
4. Substation Electrical Parameters
5. Trolley Impedances
6. Vehicle Starting Currents, Induced Line Ripple, Jerk Rates, di/dt and Top Speed.
7. Transients (Overvoltages, overcurrent, lightning, switching surges and fault behavior)
8. System Configuration
9. Clearance Requirements
10. Propulsion and Auxiliary Design

Installed substation capacity for electrified railroads for both suburban and main line service throughout the world lies in the range 120 kW - 670 kVA per single track mile (s.t.mi.).⁽⁶⁾ A study of future requirements on the Northeast Corridor indicates capacity of 650-875 KVA per s.t.mi. for low and high demand respectively. For the purpose of this study, a capacity of 500 kW/s.t.mi. was chosen as typical for future HVDC installations. Likewise, ampacity for electrified railroads with overhead trolley is in the range⁽⁶⁾ 750-1350 amps.

Conceivably, this ampacity, which is based on a wire temperature rise of $50C^0$ can be increased slightly by increasing conductivity (and cost of the catenary installation) and perhaps by increasing the allowed temperature rise. For the purpose of this study, the ampacity of 750-1500 amps per single trolley has been chosen. It is expected that mechanical considerations may limit the upper value of ampacity.

Having chosen the ampacity and capacity ranges per single track, the remaining parameters which are used in the study may be computed. These are listed in Table 1.

Trolley conductivity is based on ampacity. Generally, the conductivity is the sum of the conductivities of catenary, auxiliary catenary, and contact wire. A typical overhead trolley is shown in Figure 3.

Substation spacing is based on the requirements for 0.5MM/s.t.mi. capacity. Spacing may be more restricted because of voltage regulation, reliability and protection requirements. These cannot be determined until a real system is considered.

Inductance was determined by noting that the trolley is typically 25 ft. above the rail. Taking into account that several rails carry the return current and mutual inductive effects for adjacent trolleys in the same circuit, a range of 1-3 mH/s.t.mi. was used.

Maximum fault current and maximum rate of rise of fault current can be limited by the substation equipment design. The ranges shown in Table 1 are typical for this kind of equipment. (11)

TABLE 1 HVDC POWER DISTRIBUTION PARAMETERS USED IN STUDY

	10		25		50	
	0.75	1.5	37.5	75	150	300
NOMINAL DC VOLTAGE (kV)	10		25		50	
CONTINUOUS CURRENT (kA/s.t.)*	15		37.5		75	
SUBSTATION CAPACITY (MM/s.t.)**	15		37.5		75	
SUBSTATION IMPEDANCE (%/s.t.)***	5 - 12	5 - 12	8 - 12	8 - 12	8 - 12	8 - 12
SUBSTATION INDUCTANCE (mH/s.t.)	1.7 - 4.2	0.9 - 2.1	7.2 - 13.3	3.5 - 6.6	14 - 26.5	7.2 - 13.3
FAULT CURRENT LIMIT (kA/s.t.)	15 - 6.3	30 - 12.5	9.4 - 5	18.8 - 10	9.4 - 5	18.8 - 10
RATE OF RISE OF FAULT CURRENT (MA/s.s.t.)+	5.9 - 2.4	11.1 - 4.8	3.5 - 1.9	7.1 - 3.8	3.5 - 1.9	6.9 - 3.8
SUBSTATION SPACING (mi)**	15	30	37.5	75	75	150
CIRCUIT CONDUCTIVITY (MCM/s.t.)+++			.35	1.35		
CIRCUIT INDUCTANCE (mH/s.t.mi.) ⁰			3.0	4.0		

* MAXIMUM VALUE IS BASED OVERHEAD TROLLEY CAPACITY, AT 50C⁰ RISE

** NOMINAL DC VOLTAGE X CONTINUOUS CURRENT

*** REFERENCE 12

+ FAULT OCCURS AT SUBSTATION FEEDER BUS

++ TO PROVIDE 0.5 MM/s.t.mi. CAPACITY. VOLTAGE REGULATION MAY FURTHER LIMIT SUBSTATION SPACING.

+++ CONDUCTIVITY OF AN EQUIVALENT CROSS SECTION OF INTERNATIONAL ANNEALED COPPER STANDARD (IACS) IN MILLION OF CIRCULAR MILS

⁰TROLLEY INDUCTANCE IS VERY DEPENDENT ON CONFIGURATION OF POWER DISTRIBUTION SYSTEM.

Note: s.t. = Single Track

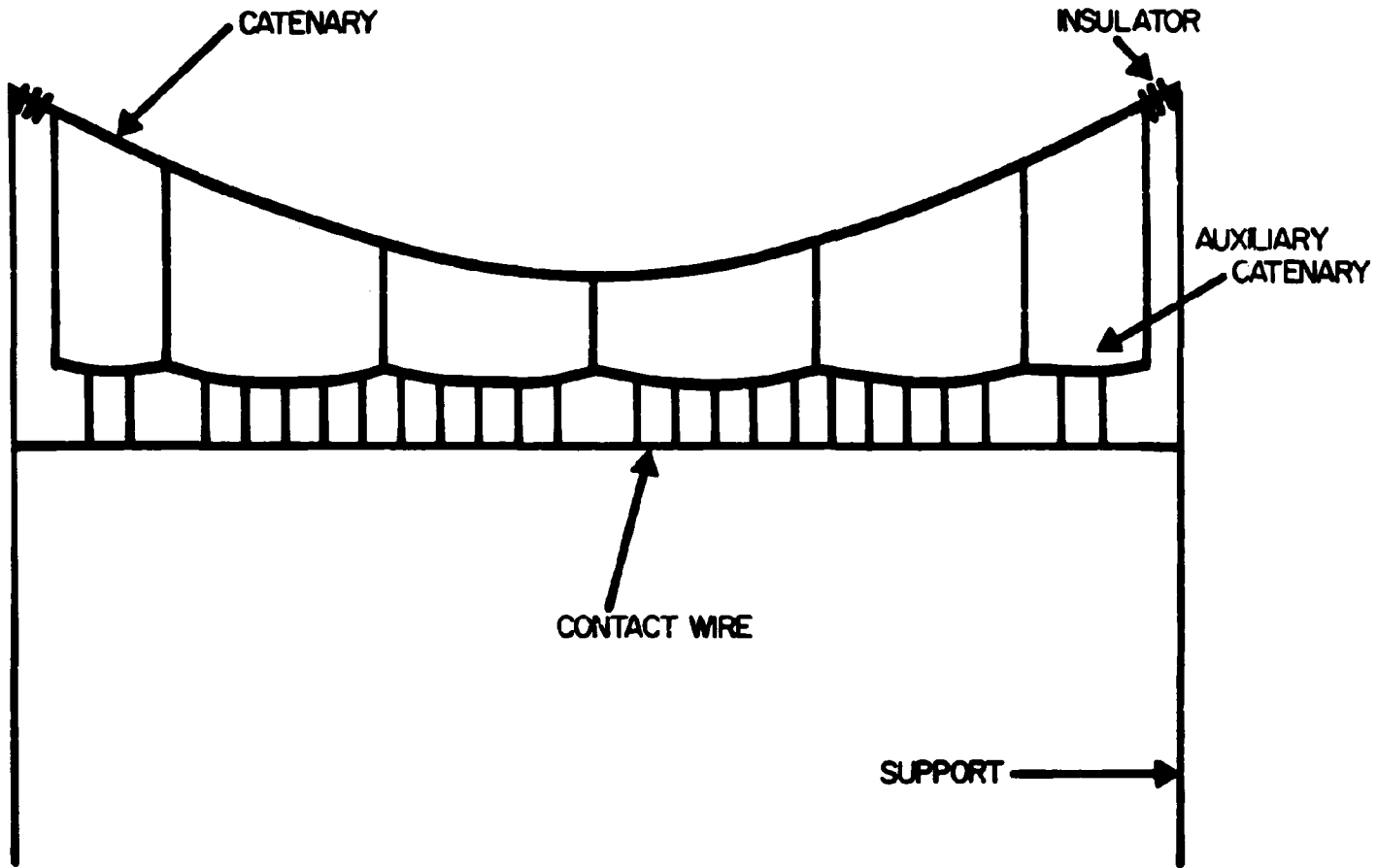


Figure 3 Composition of the Overhead Trolley

4.0 DC SWITCHGEAR FOR HIGH VOLTAGE APPLICATION

4.1 GENERAL REQUIREMENTS

A circuit breaker in the power distribution system of an electrified railroad serves three basic functions:

1. Circuit Protection by Fault Interruption,
2. Circuit Isolation,
3. Load Switching.

The most severe duty on any circuit breaker occurs during fault interruption. Circuit isolation is the disconnecting of a circuit from its power supply or from other circuits. This function is needed to perform corrective or preventive maintenance and to deenergize the circuit for safety reasons. Fundamentals of circuit breaker application are contained in an excellent series of review articles in the IEEE Spectrum⁽¹⁰⁾.

A circuit breaker has four basic requirements:

1. It must carry the continuous current of the circuit with little energy loss.
2. In its open position it must be a good insulator.
3. It must be able to interrupt any fault current without producing over-voltages which have an adverse affect on the system. In some cases, it may be required to limit fault current.
4. It must be able to close even under short circuit conditions without damage.

The interruption of DC is more difficult than the interruption of AC at comparable voltages and currents. An AC circuit breaker usually interrupts near a current zero. Ideally, an AC breaker doesn't require much arc voltage drop during the current part of the cycle, but must develop the ability to withstand voltage very quickly after current zero. In contrast, a DC circuit

breaker must create a current zero in the circuit while the fault current is flowing and hold it long enough to develop the capability to withstand voltage. Thus, the DC breaker must have a greater energy absorption capability than the equivalent AC breaker.

Two very general classes of circuit breakers are recognized:

1. Those which depend on creation and recombination of ions and electrons within solid materials to effect conduction and insulation (Solid State),
2. Those which depend on the insulating properties of vapors or gases for insulation and the properties of plasmas for conduction. (11)

The four basic circuit breaker requirements can be restated in specific tasks which can be accomplished by the same or several circuit elements. These tasks are:

1. To carry the normal circuit currents,
2. To create a current zero for some finite time during the interruption of a fault,
3. To provide insulation against system voltage and countervoltage in a very short time,
4. To absorb much of the fault energy, thus, minimizing system counter-voltage,
5. To revert from insulator to conductor without damage even under short circuit conditions.

There are several parameters which characterize HVDC circuit breakers, operating in power distribution systems. These parameters are:

1. Continuous Current
2. Continuous Voltage
3. Maximum Fault Current
4. Operating Time
5. Time to Clear Fault
6. Energy Absorption Capability
7. Magnitude of Countervoltage
8. Number of Operations Between Replacement or Maintenance.

The operating time for a circuit breaker in a power distribution system is the time from fault detection to the time at which the maximum value of fault current is reached because of circuit breaker action. Fault current can also be limited by the supply as well.

The time to clear the fault is the time from detection of the fault to the point where the circuit current is reduced to zero. This is an important parameter because it represents the length of time circuit elements within the fault are subjected to the effects of fault current.

The energy absorption capability of the breaker is the fraction of the fault energy absorbed, namely, the magnetic energy stored in the inductive circuit elements plus the input energy from the supply over the length of time to clear the fault. The amount of energy that is not absorbed will appear as an overvoltage on the system.

In practice, calculation of required circuit breaker performance is not simple. Factors which contribute to the increased complexity are:

1. Several breakers operating simultaneously,
2. Mutual inductive effects of parallel trolleys,
3. Behavior of the power supply under short circuit conditions,
4. Transients caused by the application of the fault itself,
5. Capacitive coupling in the circuit.

The magnitude of overvoltage expected determines the basic impulse level, (BIL) of the system. It affects such things as wayside insulator size and clearance requirements and insulation of substation equipment as well as filter and insulation requirements aboard the powered vehicles.

Table 2 lists some rough estimates of breaker energy absorption requirements and resulting countervoltages expected if the breaker absorbs total energy for a very simple case of a fault on the substation bus. The assumptions are listed in the appendix. The operating time of the breaker is 10 ms. This is the time to limit the fault current. For the configurations shown in Table 2, the current is limited by the circuit, itself within 2 ms.

In actual practice, however, it is not possible for the breaker to absorb all the energy. The inability of the breaker to absorb the circuit energy will result in much higher overvoltages due to the transfer of energy between circuit inductance and capacitance. Faults which occur further away from the substation will require less energy absorption capability provided these faults be detected within a reasonable time.

Faults which occur at points between substations will be difficult to detect on overcurrent at the lower voltages because the fault current may be less than twice the rated current of substations. It will be necessary to detect these faults on rate of rise. Table 3 shows a comparison between fault currents and train acceleration for faults midway between substations. Again, a single power source per trolley is used.

TABLE 2: HVDC BREAKER ENERGY ABSORPTION REQUIREMENTS AND COUNTERVOLTAGES

SYSTEM VOLTAGE (KV)	CAPACITY (MVA/s.t.)	IMPEDANCE	MAXIMUM FAULT CURRENT (kA/s.t.)	ENERGY ABSORPTION-MJ @CLEARANCE TIME		COUNTER VOLTAGE-kV @CLEARANCE TIME	
				20 ms	40 ms	20 ms	40 ms
10	7.5	5	15	2.1	3.6	13	11
		12	6.3	0.9	1.6		
	5	30	4.2	7.2			
	12	12.5	1.8	3.2			
25	18.75	8	9.4	3.4	5.7	32	27
		15	5.0	1.9	3.1		
	8	18.8	6.8	11.4			
	15	10	3.8	6.2			
50	37.5	8	9.4	6.6	11.5	63	54
		15	5.0	3.6	6.1		
	8	18.8	13.2	23.0			
	15	10.0	7.2	12.2			

Notes: Trip current is set at four times rated current for 10kV, three times rated current for 25kV and twice rated current for 50kV. This would represent the kind of short time loads one would expect on the system. Fault current is limited by circuit impedance.

TABLE 3: COMPARISON OF CURRENT DRAWN AND RATE OF RISE FOR FAULTS MIDWAY BETWEEN SUBSTATIONS AND ACCELERATING TRAINS

SYSTEM VOLTAGE (kV)	SUBSTATION CAPACITY (MW/s.t.)	ACCELERATING TRAIN CURRENT* (kA)	RATE OF RISE OF ACCELERATING CURRENT*(kA/ms)	FAULT CURRENT LIMIT** (kA)	FAULT CURRENT RATE OF RISE (kA/ms)
10	7.5	4.5	.013	4.4	.66
	15	4.5	.013	2.3	.34
25	18.75	1.8	.005	4.4	.66
	37.5	1.8	.005	2.3	.34
50	37.5	0.9	.0025	4.4	.66
	75	0.9	.0025	2.3	.34

* Based on a 16 car self-propelled train set accelerating and requiring 45 MW at a jerk rate of 2.5 MPH/SPS (rise time = 0.12 sec.)

** Using resistance of 0.3 Ω /mi. and load is fed from both ends. Inductance is 2 mH/mi.

The interruption of faults is severe duty for the breaker. A measure of breaker performance is how well it can stand up to fault interruption. It is measured by the number of fault interruptions and severity that the breaker can withstand between maintenance or until replacement. The number of fault interruptions between maintenance together with average cost of maintenance or replacement will contribute directly to the operating cost.

4.2 CONVENTIONAL SWITCHGEAR

The term "conventional switchgear" refers to circuit breakers which have been used in the past for application to either railroad or electric utility power distribution systems. This switchgear would include:

1. High Speed DC Circuit Breakers,
2. AC Circuit Breakers (Magnetic/Air Blast or Air Blast),
3. Oil Circuit Breakers.

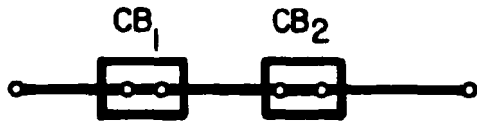
Circuit breaker configurations in which these breakers might be used are shown in Figure 4.

Figure 4.1 shows a circuit breaker composed of two conventional circuit breakers as elements in series. This scheme might be applied to voltages in the range 10-25 kV.

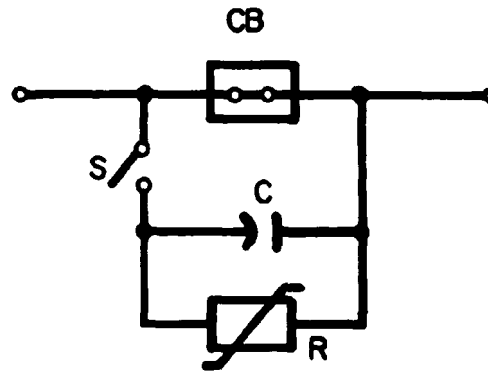
1. Two high speed DC breakers (3kV), which are suitably modified to increase arc voltage capability and to withstand the BIL level of the system, might be applied for DC voltages at the lower limit of 10 kV. Present DC high speed breakers* now have arc voltage capabilities of 8 KV.

2. AC Breakers of the magnetic and air blast variety, whose poles have been connected in series may also serve this application. Although it is difficult to estimate at this time, breakers in the 46-69 kV class may be required for DC systems of 10kV. It may also be possible to obtain the required interruption

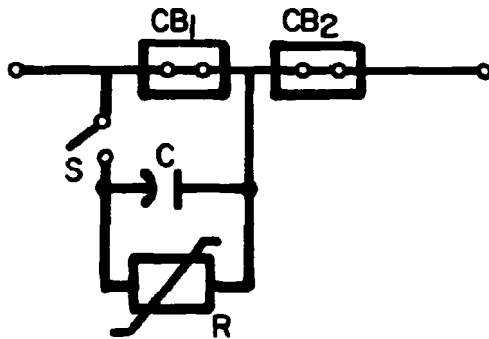
* Westinghouse Type DM-1 for example.



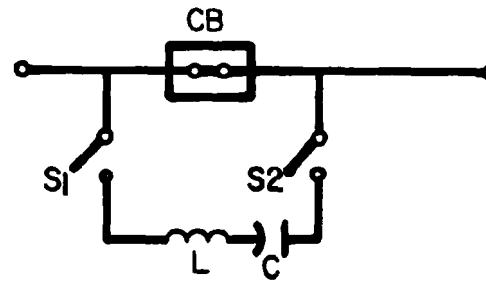
4.1 Conventional Circuit Breakers in Series



4.2 Circuit Breaker with Capacitor and Nonlinear Resistor



4.3 Series Circuit Breaker with Capacitor and Non-Linear Resistor



4.4 Circuit Breaker with Commutating Circuit

Figure 4 Circuit Breakers Using Conventional Circuit Breakers as Elements.

duty using only one such breaker rather than two in series.

3. AC Oil Breakers, suitably modified and whose poles have been put in series may also be applied. Again, higher voltage classes may be required and a single breaker rather than two in series may fit the application.

In the scheme of Figure 4.1, there is no provision for energy absorption other than that in the arc chute and gases in the air blast breakers and in the oil for the oil breakers. As a result, high countervoltages could be generated when the arc is extinguished.

The circuit breaker scheme outlined in Figure 4.2 may also work using suitably modified high speed DC breakers or AC breakers. Upon the detection of a fault, the circuit breaker opens creating an arc voltage. When the arc voltage has built up to nearly its limit, the switch is closed, diverting the short circuit current into the capacitor, thus temporarily robbing the arc of current. This may cause its extinction. The non linear resistor is then used to absorb the fault energy, keeping the countervoltage at reasonable levels. This scheme may be useful in the 10-15kV range with proper selection of CB, C and R. This selection would depend on actual system parameters.

The circuit breaker shown in Figure 4.3 is similar to the concept employed in Figure 4.2. Both circuit breakers are opened simultaneously. In addition, CB could remain open for purpose of isolation. This method has been tried with a special oil breaker ⁽¹³⁻¹⁵⁾ using flowing oil for arc interruption as part of an experiment for application to HVDC power transmission. At currents of 650 amps, arc voltages up to 60 kV were developed and maintained until the current was interrupted.

The concept ⁽¹⁶⁾ shown in Figure 4.4 includes a series-resonant LC circuit with a conventional air blast circuit breaker. After the contacts of CB have

been opened, switches S_1 and S_2 are closed, superimposing an oscillation on the direct current, which, through proper selection of circuit elements, could lead to a current zero. Currents up to 250 amps have been interrupted at 100 kV DC using this scheme.

It is possible that with proper selection of circuit elements and breakers, any one of the schemes described would have potential to serve as a DC circuit breaker in the ranges of currents and voltages considered in this study.

4.3 SOLID STATE SWITCHGEAR

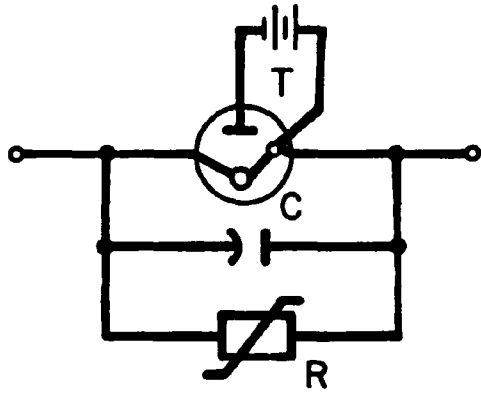
Solid state switchgear includes circuit breakers which are composed of power transistors and thyristors and associated circuitry. The solid state devices must carry the load current as well as interrupt fault current.

The relatively low power handling capability of power transistors means that many series/parallel units would be required for the job.

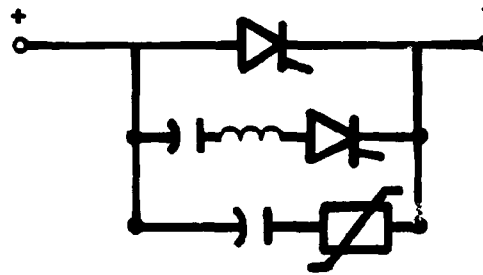
Power transistor cost is typically \$80-100/kVA and because of the rather limited overload capability, nearly the full fault MVA would be required in the power transistor unit. Furthermore, the power requirements for the base drive are 0.075-0.1 kVA per kVA. The net result is that the cost for such a breaker would be extremely high and probably out of the question.

Although the thyristor is less expensive, the cost for a circuit breaker composed of series/parallel thyristors would be very high. The commutating circuitry to turn the thyristors off would also add to the total cost. The cost of a thyristor breaker would be of the same order of magnitude as the rectifier itself.

Typical circuit diagrams for thyristor and power transistor switchgear are shown in Figure 5.



5.1 Power Transistor Unit



5.2 Thyristor Unit

Figure 5 Solid State Switchgear Concepts

The high vacuum tetrode, although not a solid state device, can be considered in the same context as the power transistor. Although it has the power handling capability in a small number of units, it requires about 0.25 kW per MW switched. It was not considered further.

4.4 METAL PLASMA SWITCHGEAR

The term "metal plasma switchgear" refers to interrupters which depend upon a metal vapor plasma and its associated instability under magnetic or electric field action to stop the flow of current. Metal plasma circuit devices which have been developed to the point of use as interrupters for HVDC distribution systems for railroads are:

1. The Vacuum Switch (VS),
2. The Liquid-Metal Plasma Valve (LMPV).

Three circuit breaker concepts will be discussed under the above two topics. Two concepts involve forced commutation of each of the devices (VS and LMPV) and the third involves magnetic commutation of the VS.

4.4.1 The Vacuum Switch

A rough sketch⁽¹⁷⁾ of the principal components of a VS is shown in Figure 6. The electrodes are made of high purity gas-free material and the ambient gas pressure in the enclosure is about 10^{-6} torr.

An arc is established in the VS by separating electrodes. Metal from the electrode surfaces is vaporized by the action of the arc. Condensed metal appears on a condensation shield. Once the arc energy is reduced to zero, the metal vapor and plasma within the interelectrode regions rapidly condenses and recombines on both the surface of the electrodes and the shield. This causes reestablishment of the original vacuum condition with its high insulation property. Recent experiments indicate that single break interrupters are capable of interrupting 25 kA in 36 kV AC circuits where the rate of rise of reapplied voltage exceeds 500 kV/ms.⁽¹⁸⁾

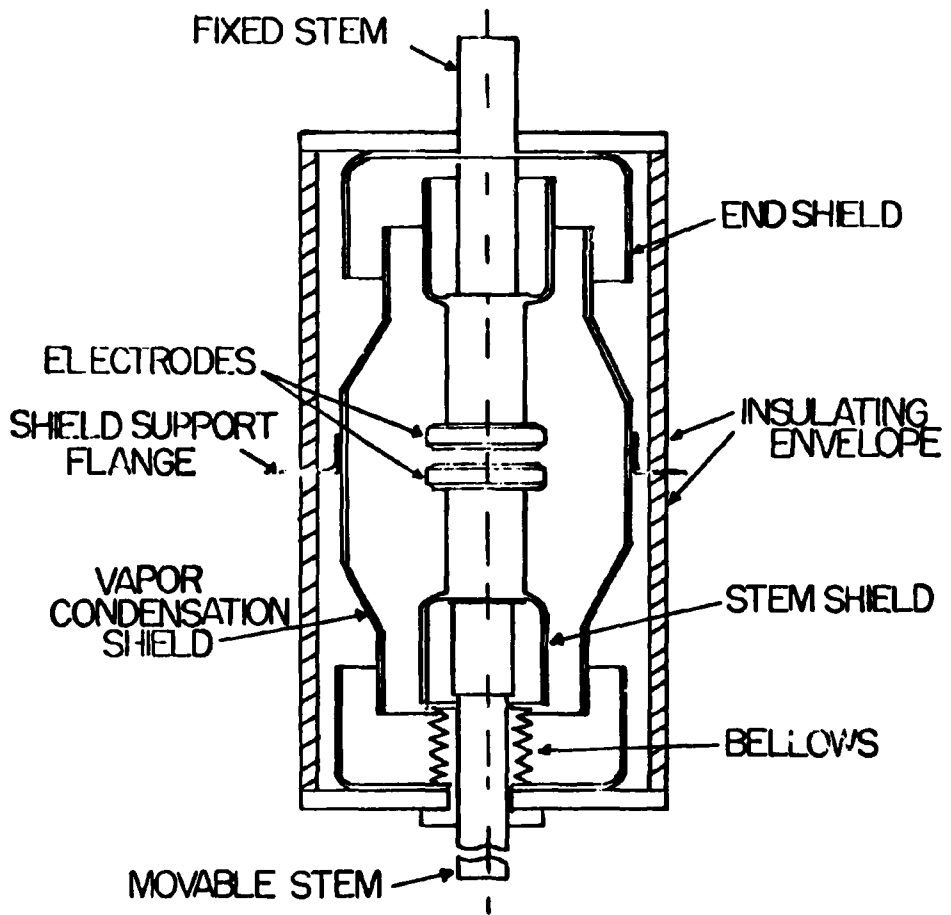


Figure 6 The Vacuum Switch

A Forced-Commutated Vacuum Switch Circuit Breaker

A forced-commutated vacuum switch circuit breaker has been considered for application to HVDC transmission networks. (19-20) Much work with this device has been done by the General Electric Co. The circuit breaker is shown in Figure 7 in a one line diagram. The capacitor, C_2 , is initially charged to line voltage. When the VS contacts are opened, the triggered vacuum gap (TVG) becomes conductive discharging the capacitor so as to drive the arc current to zero. Other elements in the circuit are:

1. The inductance, L_2 , in series with the vacuum switch is a saturable reactor. Under load current it has very low inductance. As the arc current is forced to zero once commutation is initiated, the inductance increases substantially thus controlling the circuit di/dt .
2. The combination of circuit elements L_2 , R_1 and C_1 limits the rate of rise of countervoltage so that the VS has time to regain its insulation properties.
3. Absorption of the fault energy is accommodated by a non-linear resistor, R_3 which is switched into the circuit by TVG_2 .
4. The principal of the TVG is that conduction is established between two principal electrodes by first initiating a discharge between one of them and an auxiliary electrode called a trigger. Triggered vacuum gaps behave like a VS. They generally interrupt when current through them goes to zero.
5. The residual current through TVG_2 is interrupted by switching on TGV_3 which allows the same commutating circuit to reduce the flow of current through TVG_2 .
6. The commutating capacitor C_2 is charged through the resistor R_2 to system voltage. Thus when the TVG_1 is fired, the breaker current increases first and then is later brought to zero by the commutating circuit (L_1C_2).

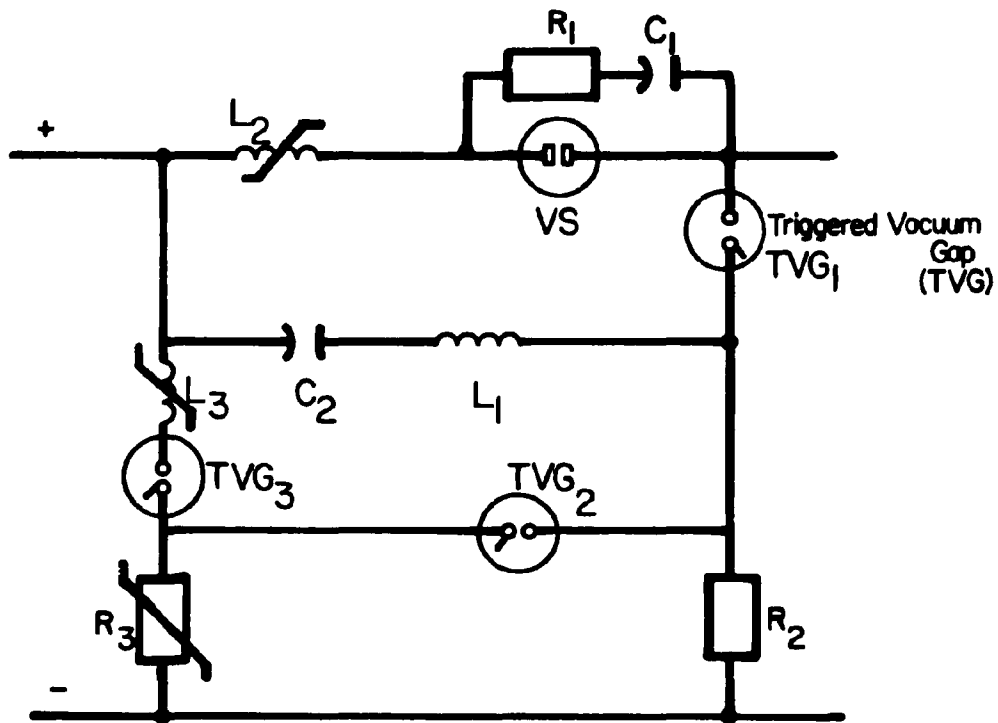


Figure 7 Forced Commutated Vacuum Switch Circuit Breaker

This circuit breaker has been tested in the laboratory under high voltage, high current conditions. It was tested at 20 kV with a single VS and at 80 kV with four VS in series. Nominal currents of 5.5 kA were interrupted. At least 15 kA was interrupted using one kind of VS. Three VS in parallel allowed interruption of currents up to 23.5 kA in circuit breakers similar to the configuration of Figure 7.

Magnetically-Commutated Vacuum Switch Circuit Breaker

Preliminary work by Westinghouse Electric Corporation⁽²¹⁾ shows that a magnetically commutated VS may hold hope for a HVDC circuit breaker in the 10-50 kV range. A schematic of such a breaker is shown in Figure 8. A strong, pulsed magnetic field is applied transverse to the electrodes of the VS as they are opened.

Commutation ability has been studied using parallel resistors and capacitors at currents to 10 kA with a single VS. The experiments were performed at low DC circuit voltages (80 V) and 10 kV and higher in AC circuits. Although the research results have not been applied to development of a circuit breaker in the range of interest, at this point in time it may have high potential because it replaces the electric commutating circuitry with magnetic circuitry.

4.4.2 The Liquid-Metal Plasma Valve

The LMPV has been developed by Hughes Research Laboratories⁽²²⁾ and most of the application work has been directed toward converter valves. The LMPV uses liquid Mercury which is vaporized and subsequently becomes a plasma by the action of the vacuum arc. As a converter valve,⁽²³⁾ one unit can carry a continuous current of 0.6 kA at 150 kV with one minute overloads of 1 kA at 285 kV and overcurrents of 28 kA for 16 ms.

The LMPV has also been applied as a switching device. It behaves somewhat like a VS in this application. Figure 9 shows an outline drawing of an LMPV.

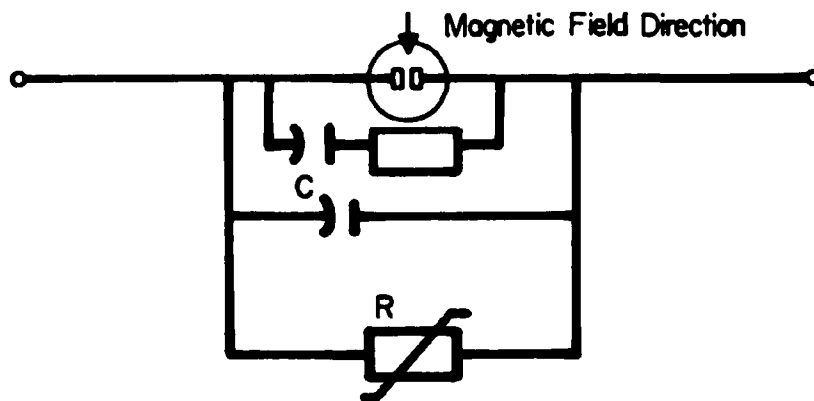


Figure 8 Schematic of Magnetically Commutated Vacuum Switch Circuit Breaker

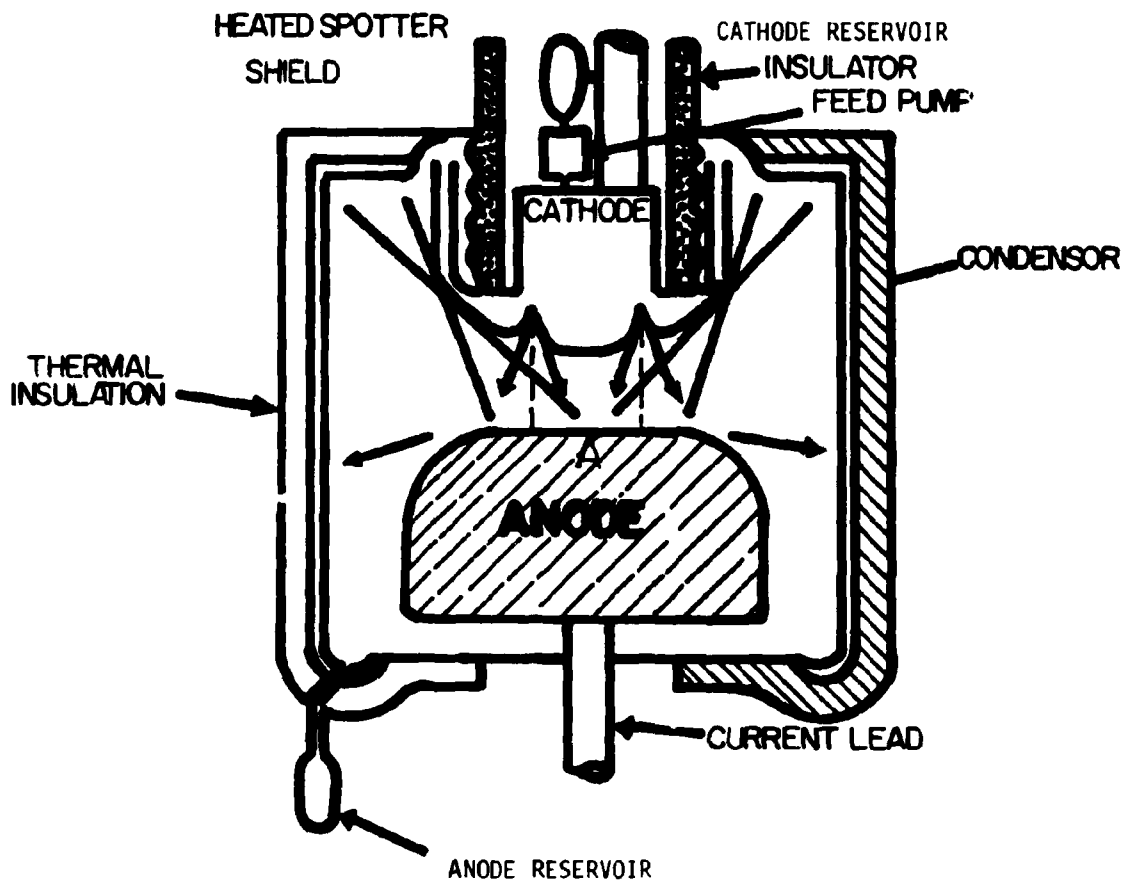


Figure 9 Liquid-Metal Plasma Valve Switch

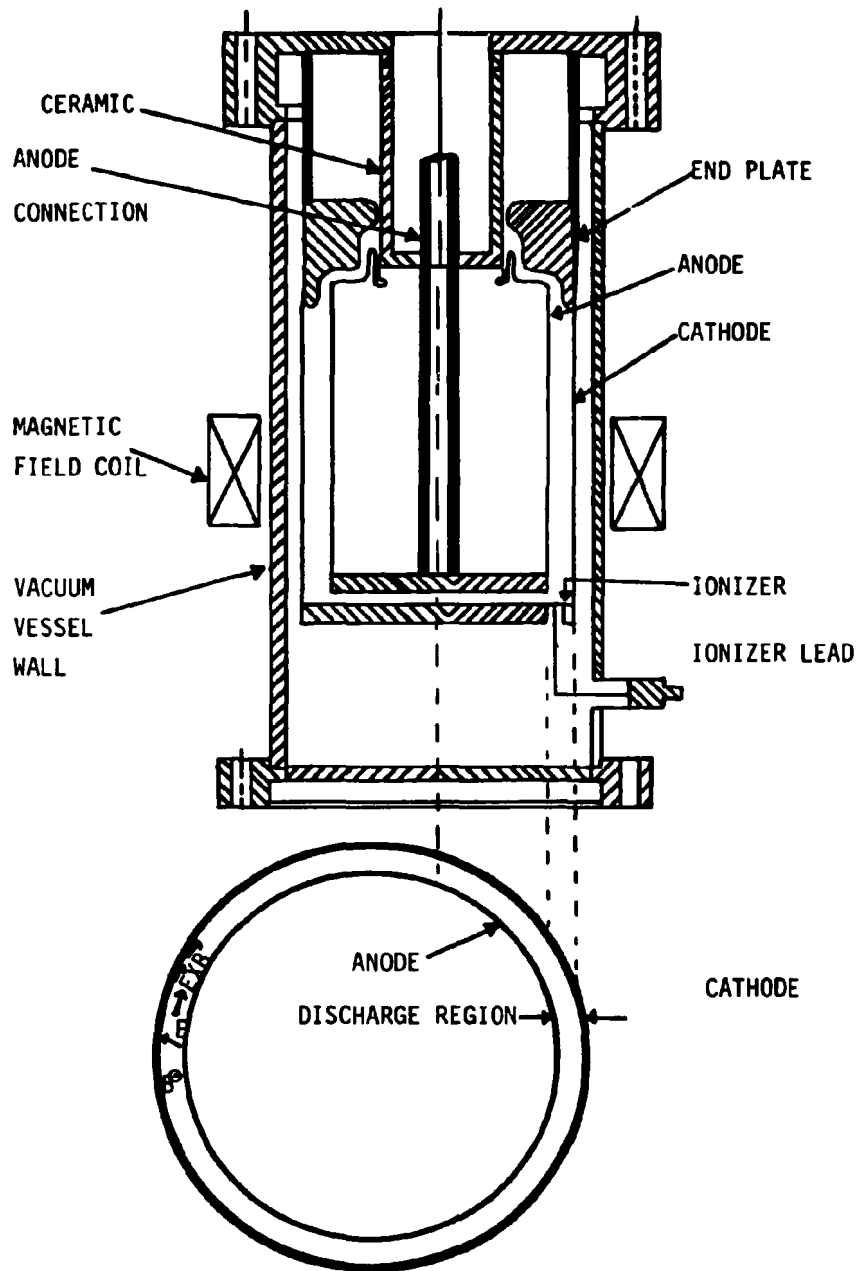


Figure 10 Outline of Cross Field Tube

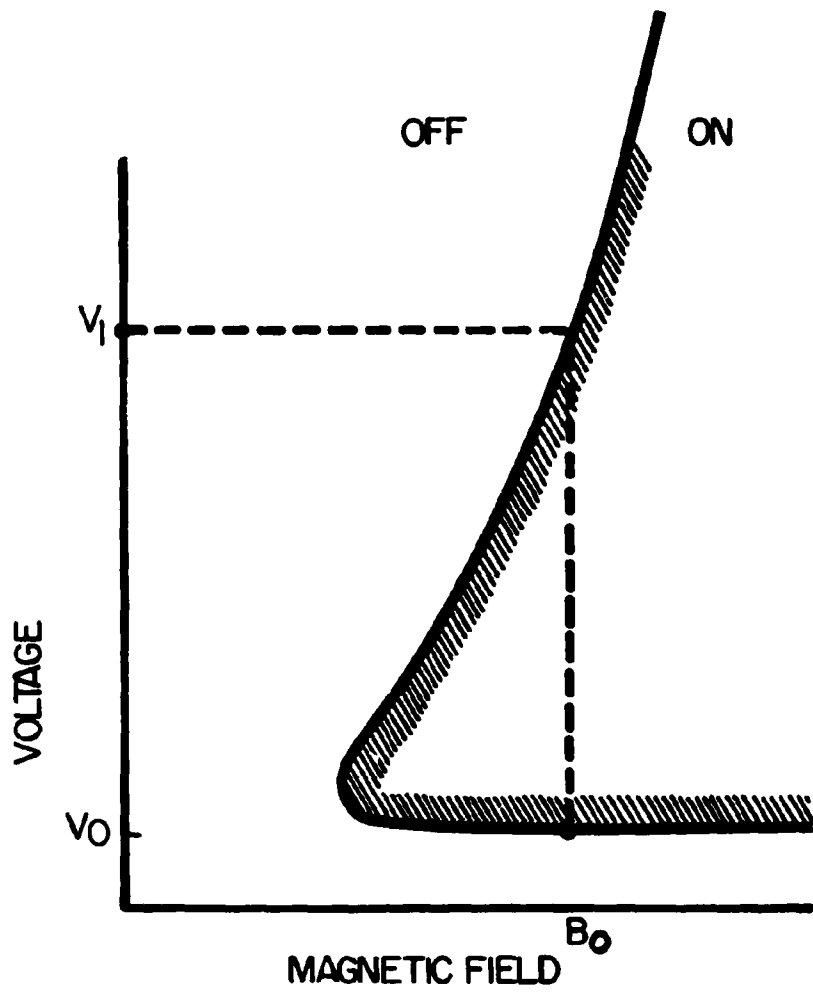


Figure 11 Cross Field Tube Operating Conditions

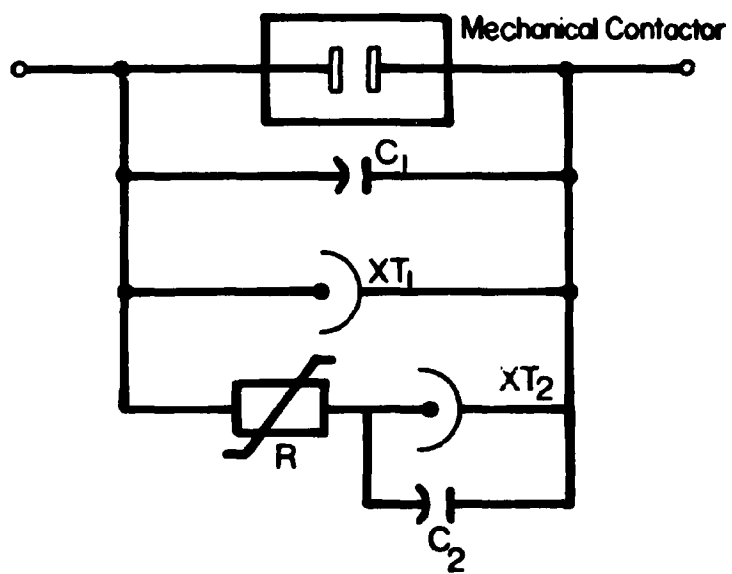


Figure 12: Cross Field Tube Sequential Circuit Breaker

mechanical contactor is immersed in Sulfur Hexafluoride (SF_6) gas which has larger arc voltage drops and better insulation recovery than air. Steps in circuit interruption are:

1. The mechanical contactor opens creating an arc voltage sufficient to put XT_1 into a conducting state. (The capacitor limits dV/dt).

2. As soon as the arc in the mechanical contactor is extinguished, the magnetic field in tube XT_1 is pulsed off causing it to go out of conduction and causing XT_2 to conduct.

3. The fault energy is now dissipated in non-linear resistor, R and as soon as fault current is at a residual value; the magnetic field in tube XT_2 is pulsed off.

Limitation on the cross field tube is the current density which it can handle. Since the tube cannot interrupt if a vacuum arc is drawn (such as in a VS) current densities are limited to about $1A/cm^2$. In a vacuum switch, current densities are of the order of $7-12 a/cm^2$. Therefore, the cross field tube is ideal for low current very high voltage applications.

4.6 QUALITATIVE COMPARISON OF SWITCHGEAR CONCEPTS

At this stage of the research effort, it is not possible to quantitatively compare the circuit breaker concepts discussed in Section 4.2-4.5. Selection of a final concept will probably be strongly influenced by the HVDC railroad power distribution system parameters.

Circuit breaker concepts involving the thyristor, power transistor and vacuum tetrode as interrupters can be eliminated from further consideration because of their high cost. Cost of a single breaker would be of the order of the substation rectifier or higher.

Because of the larger substation spacing required for economic justification of HVDC over HVAC (to offset rectifier costs), the substations will have high power per trolley fed. It is conceivable that some means external to the interrupter will be required for fault energy absorption. Therefore, only circuit breaker concepts which use a resistor or similar external device for energy absorption are included.

Table 4 lists the circuit breaker concepts which have some potential for development. They may be able to interrupt the required 10-40 kA required in the voltage range 10-50 kV.

The SF₆/Cross Field Tube commutation circuit breaker is excellent for high voltage (100 kV), low current (1 kA) interruption and has been tested in those ranges. However, as a circuit breaker in the range of currents and voltages considered here, it may prove too expensive because of the requirement for many parallel tubes (2 tubes/kA of fault current).

Oil circuit breakers may not be considered because of safety problems.

The most attractive concepts for further developments at this time are DC or AC breakers with switched capacitors or LC commutating circuits, vacuum switches with pulsed magnetic or LC circuit commutation and the LMPV with LC commutation. By considering the configuration of the substation carefully and using high speed switching devices in clever ways, it may be possible to have two or more of the interrupters share the same commutating circuit or energy absorbing resistor. This will reduce the cost per substation for these circuit elements.

This description is not the last word in DC circuit breakers. Combinations of some of the circuit breaker elements described in the preceding paragraph may prove more attractive than any of the single concepts discussed. One such idea may be a pulsed transverse magnetic field on an LMPV rather than a commutating circuit.

TABLE 4 - COMPARATIVE EVALUATION OF CIRCUIT BREAKER CONCEPTS

CONCEPT NUMBER	LOAD CURRENT CARRIED BY	LOAD INTERRUPTED BY	METHOD OF ACHIEVING CURRENT ZERO	PRO	CON	NOTES
1	DC Breaker*	DC Breaker*	°Arc Cooling °Switch and Parallel Capacitor	°Probably lease expensive scheme	°Unknown whether concept will work °Redesign of DC Breaker Required	°Would work in circuit similar to Fig. 4.2 or 4.3
2.	AC Air Breaker**	AC Air Breaker**	°Arc Cooling °Switch and Parallel Capacitor	°Could be a low cost scheme	°Unknown whether concept will work °Modification of AC Breaker Required	°Would work in circuit similar to Fig. 4.2 or 4.3
3.	AC Oil Breaker**	AC Oil Breaker**	°Arc Cooling °Switch and Parallel Capacitor	°Could be a low cost scheme °Has worked at higher voltages, lower current	°Special Breaker may be required °Oil may present safety implications.	°Would work in circuit similar to Fig. 4.2 or 4.3
4.	DC Breaker *	DC Breaker*	°LC Commutating Circuit	°	°Redesign of DC Breaker Required. °Untested	°Would work in circuit similar to Fig. 7 with breaker in place of VS
5.	AC Air Breaker**	AC Air Breaker**	°LC Commutating Circuit	°Has worked at higher voltages, lower currents	°Modification of AC Breaker required	°Would work in circuit similar to Fig. 7 with breaker in place of VS.
6.	AC Oil Breaker**	AC Oil Breaker**	°LC Commutating Circuit		°Oil may present safety implications °Untested	°Would work in circuit similar to Fig. 7 with breaker in place of VS.
7.	Vacuum Switch	Vacuum Switch	°LC Commutating Circuit	°Has been laboratory tested in voltage and current range	°It may be expensive	°See Figure 7
8.	Vacuum Switch	Vacuum Switch	°Pulsed Magnetic Field °Parallel Capacitor	°Eliminated Commutation Circuit and Control	°Untested at HVDC	°See Figure 8
9.	LMPV Switch	LMPV Switch	°LC Commutating Circuit	°Laboratory Tested at System Voltage and Current	°LMPV Switch may be more expensive than vacuum switch	°Could be used in circuit similar to Fig. 7
10.	SF ₆ Switch	SF ₆ Switch	°Cross Field Tube °Parallel Capacitor	°Field Tested at much higher voltage and substantially less current °Requires no external switch	°Would require several parallel cross field tubes to handle fault current.	°Figure 12

* DC Fast Breaker design which includes insulation to system voltage. Present DC breakers can be used to 3 kV.

** Poles of AC breaker tied in series and suitably modified to prevent arc shortening. Higher voltage rating is probably required for better arc cooling.

5.0 RECTIFIERS FOR HVDC APPLICATION

5.1 GENERAL

The rectifier substation used for the electrified railroad with HVDC power distribution may include a voltage adjustment capability to improve voltage regulation. The use of such a feature will depend on the overall economics of the power distribution system. Voltage adjustment may be provided by using a load tap changer in conjunction with the substation transformer or by having adjustment capability in the rectifier.

Four basic types of rectifiers should be considered for HVDC power distribution substations. These are classified according to the kind of electrical "valve" used to convert AC to DC. These four valves are:

1. Diode,
2. Thyristor,
3. Mercury Arc,
4. Liquid Metal Plasma Valve.

The term "valve" is used in this context because of the similarity to the valves used in HVDC transmission.

A rectifier composed of diode valves is probably the simplest and least expensive, however, it has no voltage adjustment capability. Thus, if voltage adjustment is desirable for economic reasons, the capability would be provided in the substation transformer.

The remaining three types of valves do have voltage adjustment capability. Combinations of any one of these valves together with diode valves will provide some degree of voltage adjustment. Figure 13 provides an illustration of a three phase bridge rectifier in three different configurations from least to most expensive. Voltage adjustment capability is shown. Fault protection on the DC side of the rectifier would also be provided in the case of the controlled

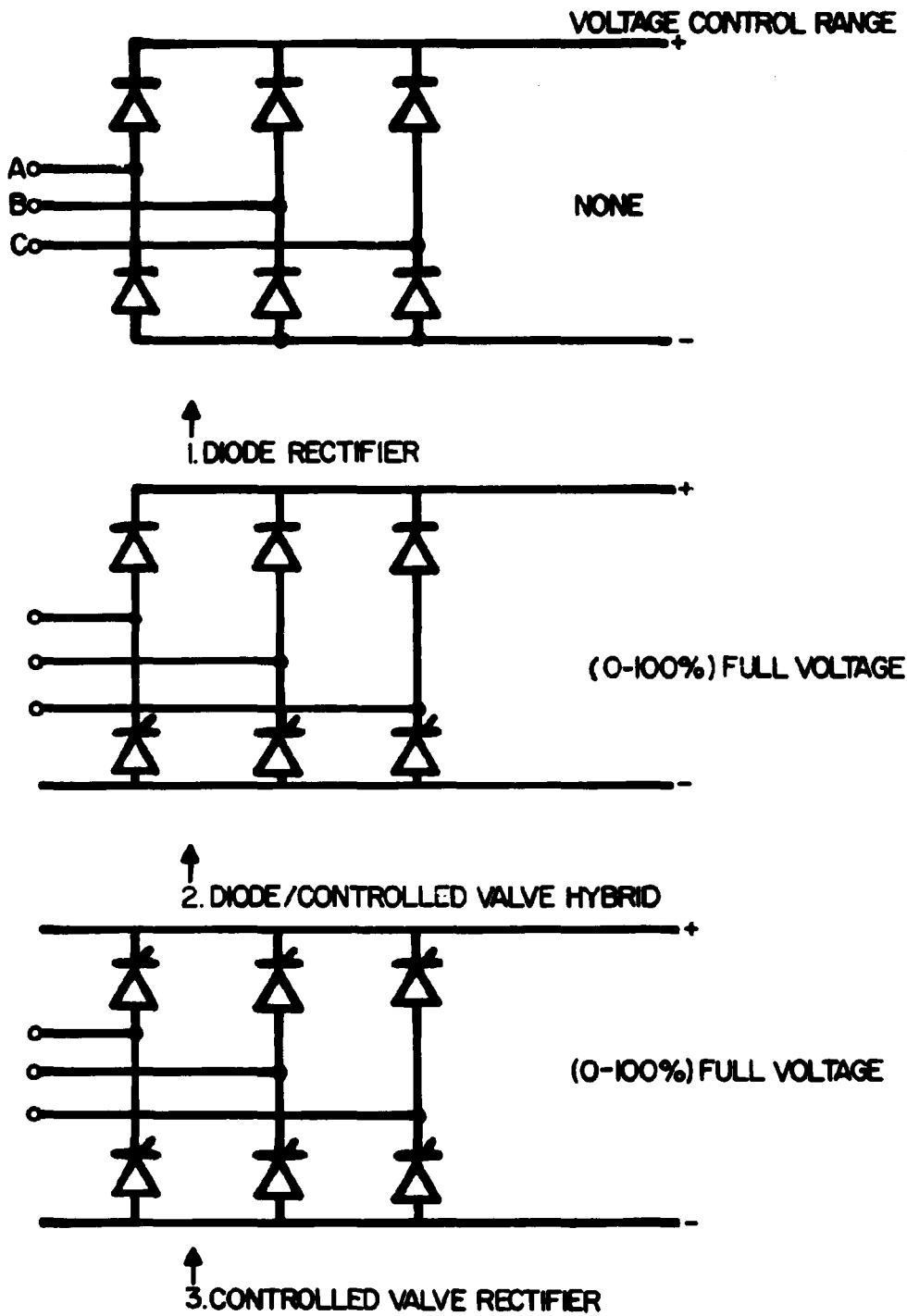


Figure 13 Three Configurations of Rectifier

valve rectifier of Figure 13. The fault could probably be detected within the first cycle and disconnected within the second cycle. Provision must be made to prevent overvoltages.

Although a three phase bridge rectifier was considered to show voltage adjustment capability, this application could call for a 6-12 phase unit. For higher phase rectification, voltage control may be provided in even less expensive hybrids.

Diode valves for the current and voltage range of this study are within the state of the art.

5.2 THYRISTOR VALVE

The thyristor valve⁽²⁶⁻²⁷⁾ is now being applied to HVDC transmission converters at voltages above 100 kV. Long strings of thyristors in series are required to meet the high voltage requirements. Either parallel strings or strings of parallel thyristors are used to meet the current carrying requirements. During the design of such a valve, precautions are taken to adequately assure proper current and voltage division. Adequate safety margins in current, voltage, di/dt and dV/dt are also provided.

The design of a thyristor valve for HVDC railroad power distribution is somewhat different. With modern current and voltage ratings it is expected that one series string will be required. Two parallel strings may be necessary for reliability reasons. About one thyristor per kV of DC voltage would probably be applied. Faults are expected to be more numerous and thyristor duty requirements may be higher.

5.3 MERCURY ARC VALVES

Mercury arc valves⁽²⁸⁾ have been used in HVDC transmission for many years and their diode counterpart, the mercury arc rectifier is used in railroad and

rapid transit application. A single mercury arc valve has increased in power (from 10-270 MW), voltage (from 50-150 kV) and current (from 200-1800 A) rating within the last several years. A typical grid-control mercury arc valve is shown in Figure 14.

Mercury arc valves are producing current levels in a single unit which are within the range required for this application. However, voltage levels are more appropriate to HVDC transmission.

While thyristors are very sensitive to high voltage spikes in terms of being destroyed, mercury arc valves are susceptible to arc backs. However, they are generally not damaged in the process.

5.4 LIQUID METAL PLASMA VALVE

An outline of the LMPV⁽²⁹⁾ manufactured by Hughes Research for use in HVDC transmission is shown in Figure 15. A single unit is rated at 600 amps and nominal working voltage of 150 kV. The LMPV has an arc voltage drop of 20-30 V as compared to a voltage drop of 150-200 V for an equivalent thyristor string.

Because the cathode design of this valve allows it to operate at higher electron to atom emission ratio than conventional mercury arc valves, the particle flux from the cathode is greatly reduced. This means that the plasma will decay more quickly following conduction, and as a consequence the valve should be less sensitive to dV/dt and tend to arc back less than the mercury arc valve. One problem is that the valve has much less operational experience than either the thyristor or mercury arc valve.

5.5 QUALITATIVE COMPARISON

Selection of the final configuration and valves for the rectifier will depend on system characteristics and economics. Electrical transients such as lightning strokes, switching surges and faults will play a large role in determining that decision. However, there are some qualitative comparisons that can be made at

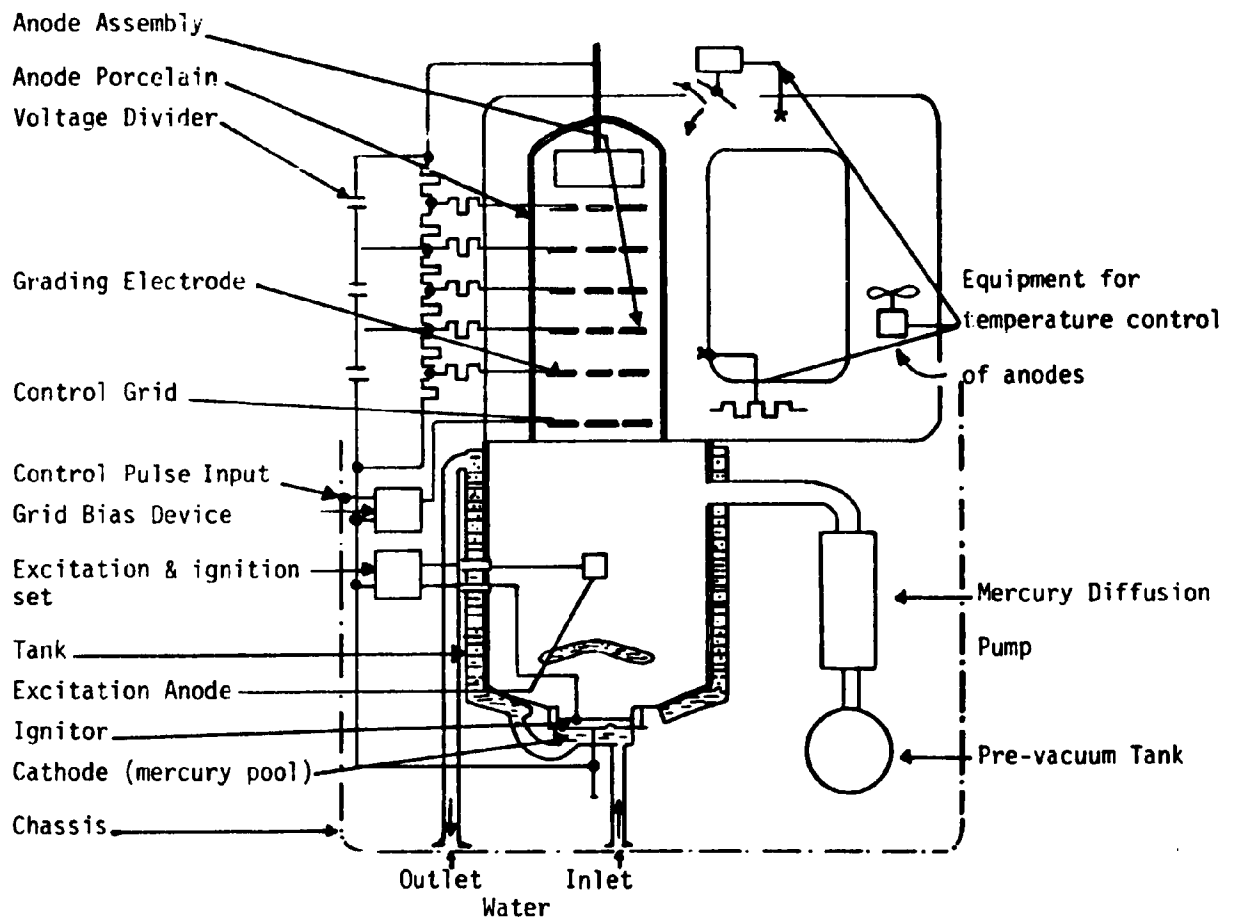


Figure 14 Mercury Arc Valve Assembly for HVDC Transmission

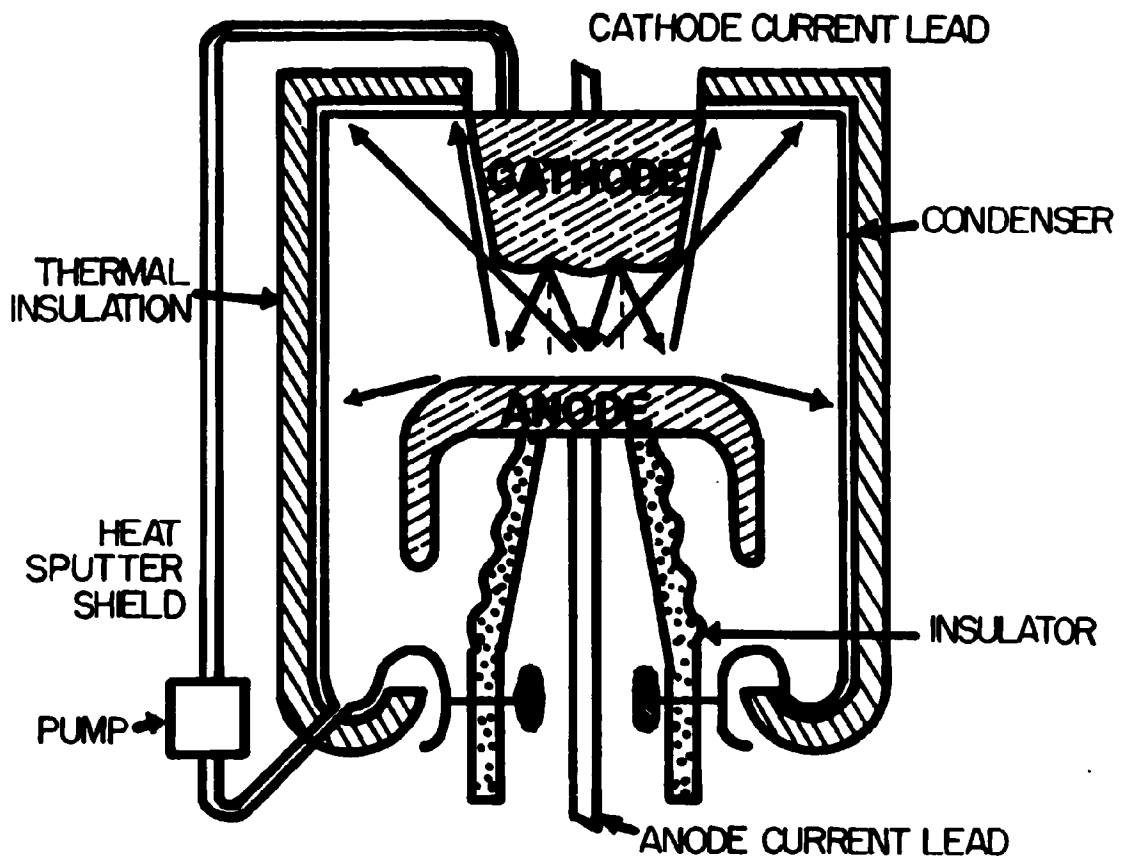


Figure 15 Liquid Metal Plasma Valve for Rectifier

this time. These comparisons are listed below:

Thyristor Valve

- Low preventive maintenance
- High corrective maintenance
- Thyristor failure monitoring required
- Low voltage drop (13 V @ 10kV; 65 V @ 50 kV)
- Some service experience in HVDC

Mercury Arc Valve

- Probably highest cost
- Low corrective maintenance
- High preventive maintenance
- Tendency to arc back
- High voltage drop (100-150 V)
- Long service experience

LMPV

- Low corrective maintenance
- Medium preventive maintenance
- Less tendency to arc back
- Low voltage drop (20-30 V)
- Little service experience

The tendency for thyristor valves in recent years to be applied to HVDC transmission converters over mercury arc valves is probably based on life cycle cost considerations. We would expect this to become more pronounced at the lower voltage range considered here. There is a large fixed cost which is independent of MW associated with the mercury arc valve. The fixed cost is much smaller for the thyristor valve since it is made up of many small units.

6.0 OPERATING PRACTICE AND EXPERIENCE

6.1 EXPERIENCE ON PRESENT PROPERTIES

Several electrified railroads throughout the world have DC power distribution systems⁽⁶⁾ which range from 600-3000 V. The Soviet Union is considering re-equipping their 3 kV DC railroad with 6000 VDC.

In order to discover potential problem areas of HVDC power distribution, it is desirable to review problem experiences on present properties which use DC distribution. To meet this objective, interviews were held with the electrical engineers of the BART system and the Erie Lackawanna railroad and the literature was reviewed. Type of experience that was sought had to do with equipment problems and suggested remedies for these problems.

6.1.1 BART System Review*

Traction power⁽³²⁾ is supplied at 1 kV through a third rail utilizing the running rail for the return path. There are 37 traction substations fed from seven utility supply points with a total capacity of 232 MW or 1.55 MW/s.t.mi. Substations have twelve phase diode rectifiers rated at either 3, 4 or 5 MW. with 7, 9 or 11 parallel diodes, respectively in each of the twelve legs. Each diode has a peak reverse voltage rating of 3 kV. Each parallel group of diodes can operate with one diode missing from the group.

Four sizes of breakers rated at 2,4,6 and 8 kA continuous and are operated on overcurrent only (300, 300, 200, 200%, respectively).

BART has good operating experience with the rectifiers. In the several years since the beginning of operation, only two rectifiers had problems. One case was attributed to a cold solder joint failure on a resistor lead and the second case to a shorted capacitor.

* Interview at BART was held with R. H. Miller, Electrical Engineer, Power and Way Division.

Experience on breaker failures has not been good. They have been running at 3-4 per year. The cause of failure has been attributed to misapplication, namely, use of a 750 V breaker which had not been properly reinsulated for service at 1 kV. The breakers can suffer from flashover on interruption. Over-voltages of 2.5 kV have been observed during interruption. Flashovers are more likely to occur when the moving contactor on the breaker is on the high voltage side of the line. As a result of the breaker problems, BART cannot operate the system in a banked secondary network and must radially feed the power. Thus the power gains from regeneration are not being realized.

Insulator flashovers along the third rail are rare. There is no noticeable accumulation of dirt or pollutants on the insulators.

Experience with wayside faults on the system has been good. 20-40 faults per year which reduces to 0.13 - 0.26 faults/s.t.mi/yr. About 90-95% are arcing faults and are associated with debris being interposed between the third rail and ground.

6.1.2 Erie-Lackawanna Railroad Review*

Traction power⁽⁹⁾ is supplied at 3 kV through an overhead trolley utilizing the running rail for the return path. There are five substations and five tie stations feeding the network of 161 track miles for a total installed capacity of 40 MW or 0.25 MW/s.t.mi. The electrical network for distribution is banked secondary.

Substation rectifiers are twelve phase and of the mercury arc type. Three ratings are used 1.5, 2.0 and 3.0 MW.

Each of the rectifier units is equipped with a negative high speed breaker which normally short circuits a load limiting resistor. On faults which occur

* Interview at Erie Lackawanna was held with R. A. Falcon, Chief Electrical Engineer.

near the substation, this breaker inserts the load limiting resistor which reduces the current to approximately full load current.

The feeder breakers, which can carry a continuous current of 2 kA, are capable of interrupting faults with a maximum rate of rise of 3 kA/ms and steady state current of 60 kA. They will trip on both overcurrent (4 kA) and rate of rise. Operating time is 0.0085 sec.

Insulators used on the catenary are normally two-bell and three-bell at stub ends. Nominal clearance is 6" to ground.

Arcbacks do occur in the mercury arc rectifiers. Ninety percent of the arcbacks are associated with the opening of a feeder breaker to clear faults immediately adjacent to the substation. The remaining ten percent of the arcbacks occur without any apparant cause. One particular substation (Roseville), has more than its share of arcbacks.

The average number of power interruptions on the system is 1644/yr. or 10.2 power interruptions/s.t.mi./yr. A good record has been kept on wayside faults and is displayed in Table 5. The high values experienced during 1971-72 was associated with field shunting on traction motors. Subsequent modifications on the motors and discontinuance of field shunting reduced the number substantially.

Breaker performance has been excellent. There have been very few breaker failures over the long history of the electrified operation.

Experience with insulators is also good. A failure rate of about one insulator per year is experienced. There has been no problem with insulator polarization until rather recently. The cause for this new development has not been determined.

By 1980, the Erie-Lackawanna as part of ConRail will change over to single phase AC distribution at 12 kV, 60 Hz.

TABLE 5 - CATENARY POWER INTERRUPTIONS ON ERIE-LACKAWANNA RAILROAD

MONTH	1967	1968	1969	1970	1971	1972	1973	1974	1975
JAN.	62	105	90	126	136	260	97	130	199
FEB.	138	58	111	103	109	305	94	149	259
MAR.	83	62	93	139	151	410	119	119	147
APR.	55	89	110	88	108	317	66	124	200
MAY	53	110	92	148	117	380*	123	146	119
JUNE	74	163	127	161	195	217**	88	76	138
JULY	117	165	144	190	279	124	103	111	198
AUG.	116	151	107	171	260	74	170	148	148
SEPT.	96	116	112	179	230	145	73	109	149
OCT.	68	108	76	143	229	75	147	150***	160
NOV.	59	72	57	134	185	110	123	172	99
DEC.	71	87	72	165	199	85	95	175	164
TOTAL	992	1286	1190	1747	2197	2502	1298	1609	1980

* Field Control in operation - 5/23/72

** Additional Control in operation - 6/5/72

***Slow Orders thru Meadows MP 2.65-MP 6.5 in effect 10/26/74

Courtesy of R. A. Falcon

6.2 PROJECTION OF EXPERIENCE TO HVDC ELECTRIFIED RAILROADS

Potential sources of difficulty for HVDC electrified railroads can be projected from experience at lower voltage. Some sources of trouble cannot be projected this way.

Rectifiers

The rectifiers could be subject to high voltage and current transients caused by lightning, faults and switching surges. Special care must be taken in the overall system design to minimize the effects of such occurrences as well as protecting the rectifiers from this transient behavior.

Fault Protection

Fault protection on a HVDC system will be difficult. Special consideration must be given to removal of the fault energy when interrupting on either DC or AC side in order to prevent high overvoltages.

Sectionalization

The ability to sectionalize the railroad power distribution system is important for both maintenance and reliability reasons. It is important that a non-clearing fault on a track section not block traffic on all tracks. Since the substation spacing will be large for HVDC, sectionalization requirements indicate that many tie stations will be required between the substations.

Clearances

Clearances between trolley and ground points must be established, once the basic impulse level of the system is determined. In part, this determination will depend on the magnitude of overvoltage experienced. It is expected that clearances would be about equivalent to RMS AC voltage clearances. This will be somewhat determined by insulator selection and maintenance practices.

Insulators

If the clearances used for HVDC are the same as for the equivalent AC voltage, there may be more of a tendency for the insulators to polarize than on

BART or the Erie-Lackawanna. This effect is not present on AC insulators because of the reversal of the electric field. This effect has not been seen on the Erie-Lackawanna (although recent observations of this condition indicates that it can happen). Polluted environments will contribute to this problem.

Arcing

DC arcs are extremely stable in air and can extend long distances. When a train moves from a live section to a dead section of wire, an arc can be carried across energizing the loads on the dead section. This is especially true if the dead section has a fault. This has happened on the Erie-Lackawanna and if the arc does not go to ground, can result in burned up catenary. Some provision in the design of the HVDC system must discourage generation of such arcs.

7.0 FUTURE RESEARCH EFFORT ON HVDC POWER DISTRIBUTION FOR RAILROADS

As a result of the work to date on the technical feasibility of HVDC for railroads, a tentative recommendation for future research and development effort has been requested.

There are five steps, which will take the work from the feasibility stage to a prototype demonstration. The last three steps are conditional and will depend on the economics of DC vs AC distribution for railroads. (Both motive power and wayside must be considered at this stage.)

1. Distribution System Parameter Identification Effort

All parameters necessary to specify a complete HVDC distribution system should be identified and their ranges determined where applicable. These would include but not be limited to:

- a. System voltage (maximum, nominal, minimum),
- b. System loads (maximum, short time, nominal),
- c. Substation spacing, substation electrical parameters, and line impedances including capacitance to ground,
- d. Vehicle parameters which affect the distribution system such as starting currents, line ripple, jerk rates, dI/dt and top speed,
- e. System transient behavior including system overvoltages, overcurrent, and other characteristics due to lightning, switching surges and faults,
- f. System configurations including two or four track, tie point requirements, methods used to decrease impedance and two or three wire distribution,
- g. Distribution system clearance requirements both through air to ground and over insulators to ground.

This study should be undertaken knowing the parameters of comparable AC distribution systems and always keeping them in the forefront. The system parameters would also be based on models of the operation of electrified systems included train consists, headways, speeds, etc. from which the electrical loadings can be establish-

ed. The program should be carried out in parallel with propulsion system development for rolling stock which must operate under HVDC catenaries.

Three sub-investigations will have to be conducted to complete this step:

- a. Electrical transient analysis should be completed on the DC and AC distribution system configurations considered. This analysis will be necessary both to specify transient-type parameter ranges (for circuit breakers, insulators, etc.) as well as to understand the system parameters which are most significant in determining transient behavior.
- b. An investigation should be carried out on DC arc behavior at these higher voltages. This investigation should be directed toward arc generation between a moving pantograph and a contact wire as well as arc damage to wire. Comparisons ought to be made with similar voltage AC arcs.
- c. The question of insulator polarization (metal particles) should be investigated at these high voltages. Experiments should be carried out on this phenomena. Again comparisons ought to be made with AC case.

The output of sub-investigations (b) and (c) would be used to select line to ground separation over air and insulators. The smaller the separation, the less expensive the distributor.

2. Study of DC Circuit Breaker Candidates

As a result of the present study, four or five circuit breaker concepts have emerged as candidates for application to HVDC railroads. These are the forced-commutated vacuum interrupter, the magnetically-commutated vacuum interrupter, the force-commutated liquid metal plasma valve, modification of a present magnetic-air breaker with energy storage and dissipation capability.

Using the ranges of system parameters generated in the Distribution System Parameter Identification effort, these prime candidates should receive further attention. The considerations and outputs of this attention should be principally economic although technical questions may arise as the system parameters are reviewed for breaker applications. The economic outputs would be development costs, production prices per unit, operating and maintenance cost. Reliability during operation and lifetime should also be basic considerations in an overall life cycle cost estimate.

In parallel with this effort, an economic and technical study should be completed on an alternative scheme for HVDC distribution using switching on the AC side and manual disconnect switches on the wayside for circuit isolation. The effect of this method on system performance should also be investigated.

3. Comparison of AC vs DC Distribution for Railroads

At this stage, after the cost data on DC circuit breakers have been generated, system parameter ranges established, alternate protection schemes for DC distribution considered and clearances have been determined, a parametric analysis of AC and DC distribution systems ought to be completed.

Motive power on board the vehicles as well as auxiliaries would be considered as part of the overall economics at this time. If DC distribution looks economically sound (perhaps 10-25% less costly than AC), then technical risks of going to DC should be made at this time, based on outputs from the two previous investigations. If the risks outweigh the rewards for a program using DC circuit breakers, then the next step should be undertaken. If an alternate concept of DC distribution is economically attractive with low risk, then step 5 should be next.

4. HVDC Circuit Breaker Development

The most attractive of the four or five candidates studied in step 2, would be recommended for further development. Both economic, operational and technical considerations would be used in this selection, although economic would probably carry the most weight at this stage of the program.

The candidates for the breakers would be designed, fabricated and tested in a laboratory. Further refinements on cost data, technical performance, reliability and maintainability in a transit environment would be obtained as part of this program. The comparison of AC vs DC distribution would be updated at this time.

5. Design, Fabrication and Testing of a Prototype DC Distribution System

If DC distribution system economics and technical performance is viable, design, fabrication and testing of a small, prototype DVDC system in a transit environment should be undertaken. Motive power capable of either running or simulated running on this system should also be available at this period in time.

Data which are obtained from this operation would be evaluated and a decision as to the technical and economic merit of HVDC for production railroads could be made.

8.0 BIBLIOGRAPHY

8.1 REFERENCES

1. Electric Power Systems for High Speed Ground Transportation, Westinghouse Electric Corporation, Final Report to Office of High Speed Ground Transportation, August, 1969.
2. Electric Power Systems for High Speed Ground Transportation, Proceedings of IEEE/IGA, Jan/Feb., 1975.
3. The D-C Breaker: Key to KVDC Expansion?, Michael Morgan, Assoc. Editor, Electric Light and Power, July 21, 1975.
4. Field Test of HVDC Circuit Breaker: Load Break and Fault Clearing on the Pacific Intertie, G. A. Hofmann et. al. IEEE PES Winter Meeting and Tesla Symposium, New York, N.Y., Jan 25-30, 1976.
5. Design of DC Power Supply for Rapid Transit Systems, Laszlo De Koranyi, Railway Gazette, October 1, 1965.
6. Power Supply for Main Line Railway Contact Systems, P.A. McGee and E. L. Harder, AIEE Winter Convention, New York, N. Y., Jan. 23-27, 1933.
7. Pennsylvania Railroad, New York-Washington-Harrisburg Electrification Relay Protection of Power Supply System, E. L. Harder, AIEE Winter Convention, New York, NY., Jan 23-27, 1939.
8. A Parametric Cost Study of AC-DC Wayside Power Systems, H. Rutishauser et. al., FRA-OR & D - 76-24, Sept. 1975.
9. General Electric Review, Issue on Erie-Lackawanna, Vol. 34, No. 11, Nov. 1931.
10. Circuit Breakers, Physical and Engineering Problems, W. Rieder, Part 1 Fundamentals, IEEE Spectrum, July, 1970, Part 2 Design Considerations, IEEE Spectrum, Aug. 1970.

11. Plasma Physics and the Interruption of an Electric Circuit, T. H. Lee
Proc. of IEEE, Vol. 57, No. 3, March 1969.
12. Electrical Transmission and Distribution Reference Book. Westinghouse
Electric Corporation, East Pittsburgh, Pa., 1950.
13. Erzeugung sehr hoher Lichtbogen­spannungen für Gleichstrom Hochspannungs-
schalter, E. Marx, ETZ-A 86 (1965), S.701-702.
14. Testing a New Type of Circuit Breaker for HVDC, K. Moellenhoff, D.
Morgen et. al., Direct Current, 11(1966) p. 3-6.
15. Circuit Breaker for HVDC - Transmission, D. Kind et. al., CIGRE, Inter-
national Conference on Large High Tension Electric Systems, Paper 13-08,
June, 1968 Session.
16. Switchgear for HVDC Lines, G. A. Kukerkov et. al., Direct Current,
Volume 4, (1959).
17. A Brief Review of Arcing and Interruption Phenomena in Vacuum, Clive W.
Kimblin, IEEE TRANS PHP-9, No. 1, Mar. 1973.
18. Some Investigations of High Current Vacuum Arcs and the Development
of 24-36 kV High Power Vacuum Circuit Breakers, H. Sugawara, and
T. Takasuna, Paper No. C 72 528-8, IEEE Summer Power Meeting, July 1972.
19. Theory and Application of the Commutation Principle for HVDC Circuit
Breakers, A. N. Greenwood, T. H. Lee, Paper No. T72 107-6, IEEE Winter
Meeting, N. Y., N. Y., Feb. 1972.
20. HVDC Vacuum Circuit Breakers, A.N. Greenwood, P. Barkan, W. C. Kracht,
Paper No. T 72-106-8, IEEE, Winter Power Meeting, N. Y., N.Y., Feb. 1972.
21. Current Commutation Using Magnetic Fields to Force Instability of
Vacuum Arcs, C. W. Kimblin et. al. Paper submitted to 1976 IEEE Inter-
national Conference on Plasma Science, Austin, TX., May 24-26, 1976.

22. DC Conversion. Rebirth of the Mercury Valve, M. Morgan, Assoc. Ed.
Electric Light and Power, July 21, 1975.
23. A 10 kA, 30 kV Liquid -Metal Plasma Valve Switch for Inductive Energy
Storage, W. O. Eckhardt and G. A. Hofmann, Sixth Symposium on Engineering
Problems on Fusion Research, San Diego, CA, Nov. 18-21, 1975.
24. The Gamitron - A High Power Cross - Field Switch Tube for HVDC Inter-
ruption, M. A. Lutz, G. A. Hofmann, IEEE, Trans, PS Vol. 2, No. 1,
March, 1974.
25. The Cross-Field Switch Tube - A New HVDC Circuit Interrupter, H.
Gallagher, G. A. Hofmann, M. Lutz, No. T. 72 531-2, IEEE, PES, Summer
Meeting, San Francisco, CA, July 9-14, 1972.
26. The Thyristor Valve in HVDC Transmission, G. Karady and T. Gilsig,
IEEE Sprectrum, Vol. 10, No. 12, Dec. 1973.
27. The Thyristor as a Component for HVDC Transmission, W. Becker et. al.
AEG-TELEFUNKEN Progress (1969)2.
28. Mercury Arc Valves for HVDC Transmission, T. E. Calverley, Direct Current
Vol. 1, No. 1.
29. D. C. Conversion: Rebirth of the Mercury Valve, M. Morgan Assoc. Edit.,
Electric Light and Power, Feb. 1975.
30. Power Semiconductors, R. Allen Assoc. Edit., IEEE Spectrum, Nov., 1975.
31. Report on the Visit to the USSR by the U. S. Electrification Delegation,
Daniel Jacenko, FRA ORD & D, May 26, June 5, 1975.
32. The Design and Operation of the BART Power System, R. H. Miller,
IEEE TRANS, IA - 10, No. 5, Sept./Oct., 1974.

8.2 ADDITIONAL BIBLIOGRAPHY

33. Statistics of Circuit Breaker Performance, J. G. Steel et. al. Proc.
IEEE, Vol. 117, No. 7, July, 1970.

34. A Study on Some Switching Aspects of a Double Circuit HVDC Transmission Line, W. F. Long, IEEE PES Summer Meeting, San Francisco, CA, Paper No. T 72, 532-0, July 9-14, 1972.
35. Fundamentals of HVDC Interruption, W. Pucher, CIGRE Electra, No. 5, pp. 24-38, June 1968.
36. HVDC Switching Devices and Arrangements, CIGRE Electra, No. 18, pp. 9-65, July, 1971.
37. A Survey of Western European AC Electrified Railway Supply Substations and Catenary System Techniques and Standards, B. A. Ross, IEEE/ASME Joint R.R. Conference, March 27-28, 1968, Paper No. 68, CP 203-IGA.
38. Lackawanna Suburban Electrification, Edward L. Moreland, AIEE Winter Convention, N.Y., N.Y., Jan. 26-30, 1931.
39. Power Supply Facilities for Reading Suburban Electrification, C. L. Doub, AIEE Middle Eastern District Meeting No. 2, Philadelphia, Pa., Oct. 13-15, 1930.
40. The Reading Company's Philadelphia Suburban Electrification, G. I. Wright, AIEE Pacific Coast Convention, Vancouver, B.C., Aug. 30-Sept. 2, 1932.
41. Railroad Electrification, Past, Present, Future, Gordon D. Friedlander, IEEE Spectrum, Nov., 1967.
42. Development of Power Supply and Supervisory Equipment for British Railway, 50 HZ A.C. Electrification, C. E. Cole, H. Roper, F. Whittaker, Proc. IEE, Vol. 119, No. 2, Feb. 1972.
43. System Design for 50 HZ A.C. Electrification, E. Claxton, B. Sandham, PROC IEE, Vol. 119, No. 2, Feb. 1972.
44. Railway Electrification, Diesel-Electric Locomotives and Some Future Aspects of Electric Traction, G. Huddschiner, Proc. AIEE, Vol. 71, 1952.

45. A. Reappraisal of the Economics of Railway Electrification: How, When, and Where Can it Compete with the Diesel-Electric Locomotive, H. F. Brown, R. L. Kimbal, AIEE Winter General Meeting, New York, NY, Jan. 18-22, 1954.
46. Current Propagation in Electric Railway Propulsion Systems, John Riordan, AIEE Summer Convention, Cleveland, OH, June 20-24, 1932.
47. Investigation of Rail Impedances, H. M. Trueblood, George Wascheck, Electrical Engineering, Dec. 1933.
48. Regulation and Inductive Effects in Single Phase Railway Circuits, A. W. Copley, Electric Journal, Aug. 1920.
49. Railway Electrification, Report on Assignment 13, AREA Bulletin No. 609, Vol. 69, Nov. 1967.
50. Railway Electrification, Discussion AREA Bulletin No. 626, Vol. 71, Feb. 1970.
51. Proceedings of Convention on Electric Traction by Single Phase Current at Industrial Frequency, Oct. 12-15, 1951, Lille, France.
52. Proceedings of Convention on Electric Traction by Single Phase Current at Industrial Frequency, Lille, France, May, 1955.
53. Design and Operation of the BART Power System, R. H. Miller, IEEE Power Engineering Society Summer Meeting, San Francisco, Calif., July 9-14, 1972.
54. HVDC: Insulation Coordination, E. Uhlmann, G. Flisberg Direct Current, Vol. 2, No. 1.

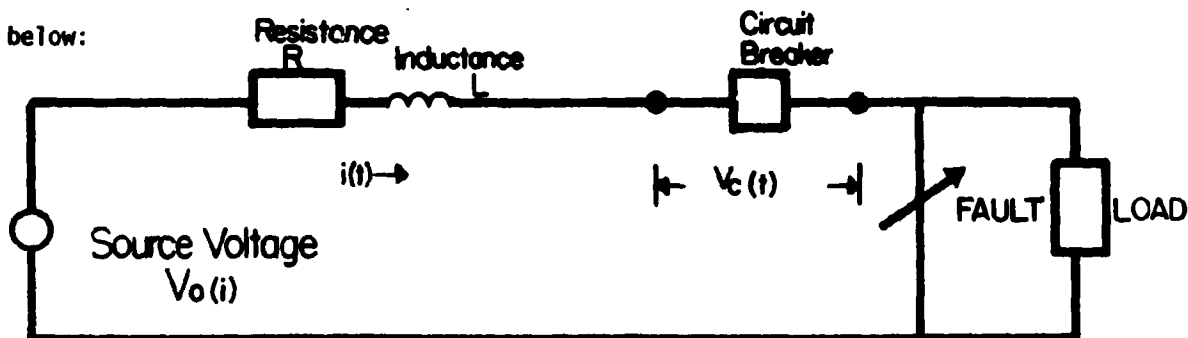
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9.0 APPENDIX: SIMPLIFIED ANALYSIS OF THE FAULT INTERRUPTION PROCESS

A simplified version of a circuit in which a DC breaker operates is shown below:



The basic equation governing the circuit has the form:

$$L \frac{di}{dt} + iR + V_c(t) = V_o(i) \quad 9.1-1$$

Fault Current Limited By Breaker

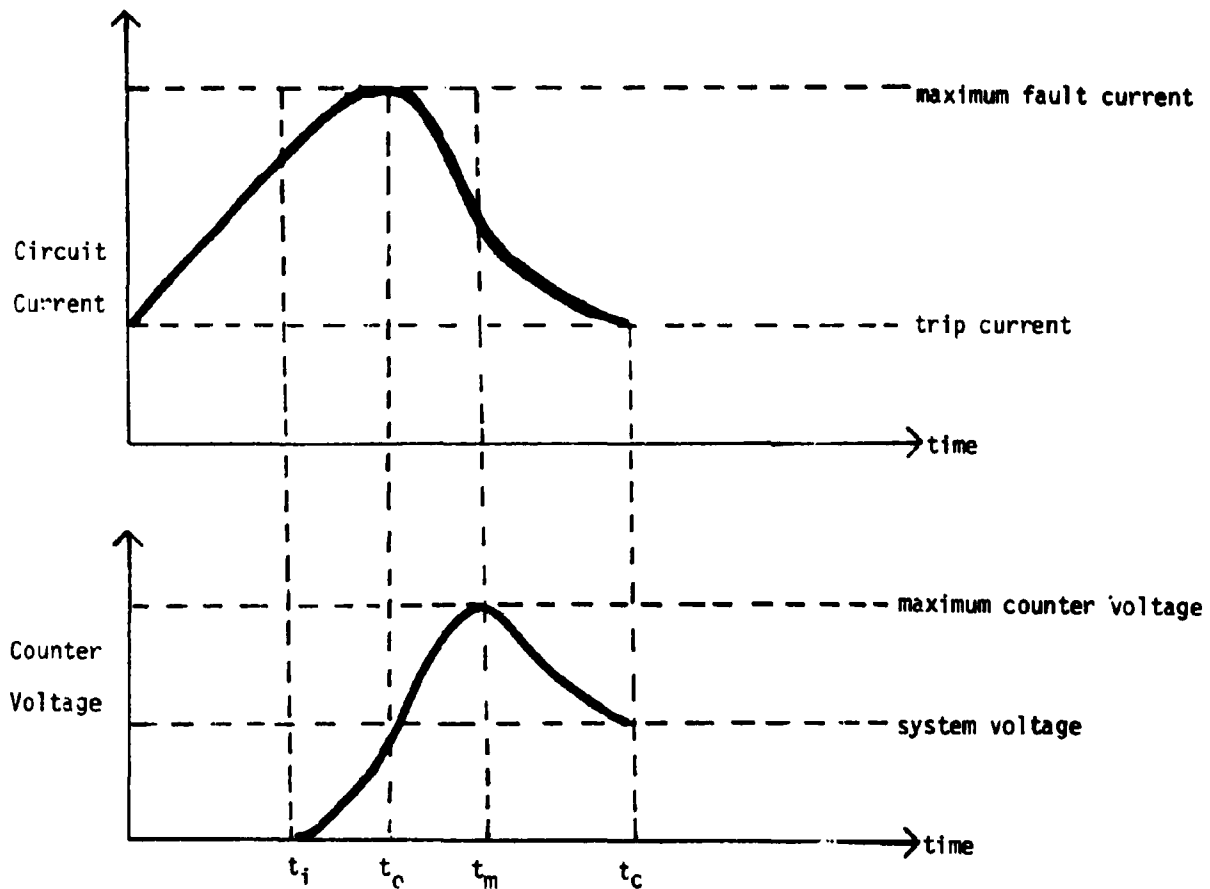
The boundary conditions are:

1. At $t=0$, the fault is detected. At this time the circuit current is just the load current, i_L .
2. At $t=t_d$, initiation of a counter voltage into the circuit by the breaker begins.
3. At $t=t_o$, the countervoltage has reached a value to limit the rate of rise of current. This is the operating time of the breaker

$$\left. \frac{di}{dt} \right|_{t=t_o} = 0$$

4. At $t=t_c$, the fault is cleared because the circuit current is reduced to zero.

The process just described is illustrated in the diagram below for a low voltage D.C. air breaker.



Note that in a normal D C breaker the countervoltage is just the arc voltage.

At t_i the contacts part. Subsequent expansion of the arc and cooling caused by the arc shield causes a steeper rate of rise of arc voltage and at t_o , the breaker operating time, the arc voltage equals system voltage, thus limiting the current.

The following statements can be made about the interruption process with the above diagram

1. The initial rate of rise of fault current is approximately

$$\left. \frac{di}{dt} \right|_{t=0} = \frac{V_0}{L}$$

2. The rectifier or source voltage drops as the fault current increases causing a negative curvature in the current vs time curve.
3. The countervoltage is initiated at time $t=t_d$. At time $t=t_0$, the countervoltage is given by the expression

$$V_c(t_0) = V_0(i_0) - i_0 R \quad 9.1-2$$

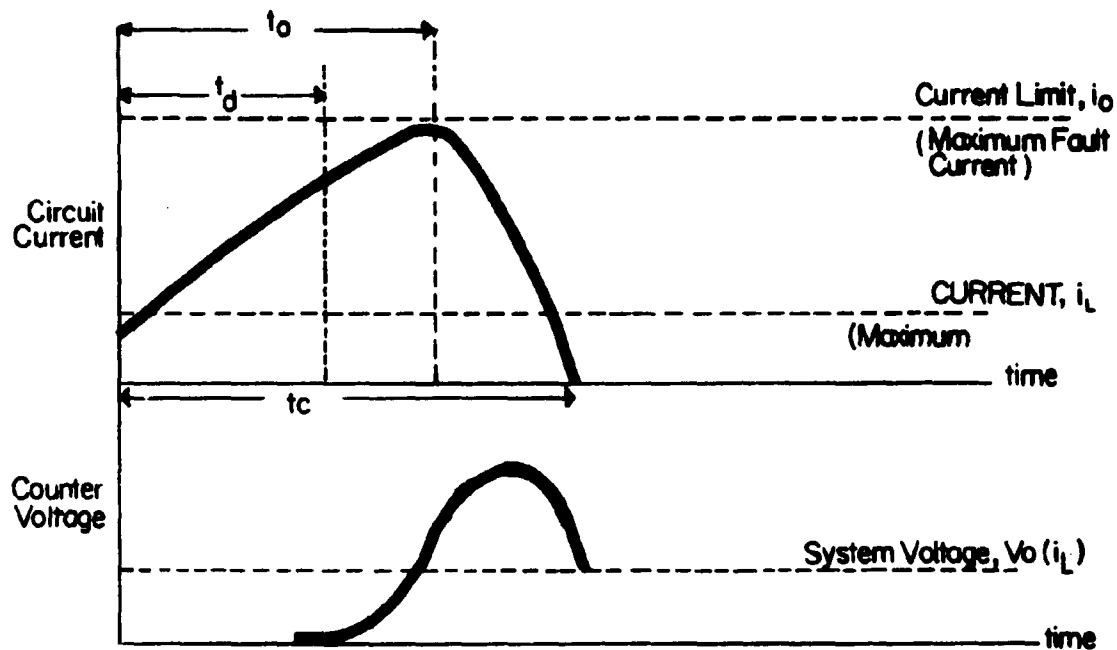
which is the point at which the fault current reaches its maximum ($i=i_0$).

4. The countervoltage is applied by the breaker until the current is forced to zero at $t=t_c$. The energy balance is given by the expression

$$\int_0^{t_c} V_c(t) i(t) dt = \frac{1}{2} L i_L^2 + \int_0^{t_c} V_0(i) \cdot i(t) dt - \int_0^{t_c} i^2(t) R dt \quad 9.1-3$$

The term on the left hand side of equation 9.1-3 is known as the switching energy, which must be absorbed by the breaker. The first, second and last terms on the right hand side of equation 9.1-3 are the magnetic, the input and the Joule loss energies, respectively. The input energy must flow through the rectifier.

The following diagram is more representative of the case of a breaker which develops countervoltage by using commutating circuits (electric or magnetic) together with an auxiliary energy absorbing device represented by a non-linear resistor.



At time $t=t_d$, the mechanical device in the breaker creates the arc, and thus arc voltage. This countervoltage remains at a very small value with respect to system voltage until nearly the operating time of the breaker, at which time the major portion of the countervoltage is applied by commutation. This is shown by the very fast rate of rise of countervoltage near $t=t_o$.

At $t=t_o$, the non-linear resistor is inserted, keeping the countervoltage at nearly a constant value until nearly $t=t_c$ at which time it is switched off quickly.

To compute the energy involved in this process, the following assumptions have been made

1. The circuit iR drop is small compared to the system voltage.
2. The rectifier voltage remains constant during the fault (conservative assumption).
3. The countervoltage is applied instantly at $t=t_o$ and remains constant until $t=t_c$ at which time it reverts instantly to system voltage.

With these assumptions equation 9.1-1 becomes:

$$L \frac{di}{dt} + V_c(t) = V_o \quad 9.1-4$$

So that until the counter voltage is applied by the breaker at $t = t_o$, the current in the circuit is:

$$i = i_L + \frac{V_o}{L} t \quad 9.1-5$$

and the fault current limit at the instant the countervoltage is applied is:

$$i_o = i_L + \frac{V_o}{L} t_o$$

$$t_o = \frac{i_o - i_L}{V_o/L} \quad 9.1-6$$

Since the effect of the countervoltage is to bring the current to zero in time $(t_c - t_o)$, the relationship can be expressed in the equation:

$$i = i_o \left(1 - \frac{t - t_o}{t_c - t_o} \right) \quad 9.1-7$$

and

$$V_c = V_o + \frac{L i_o}{t_c - t_o} \quad 9.1-8$$

is the magnitude of the countervoltage required.

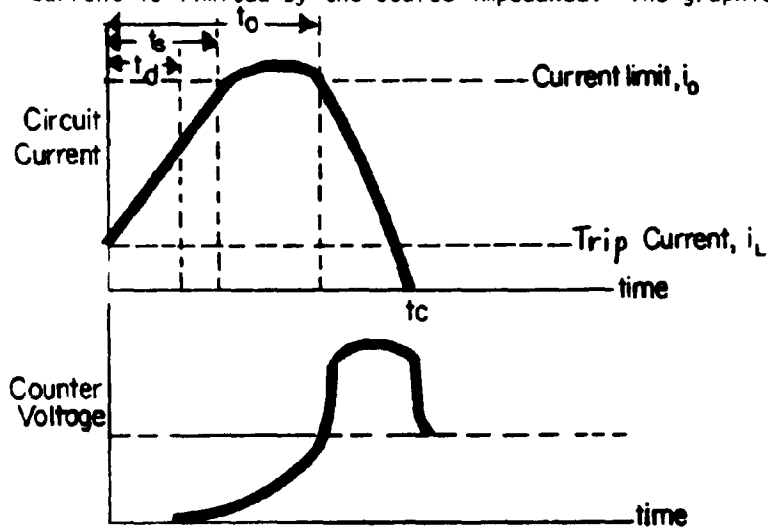
Under these assumptions, the energy absorbed by the circuit breaker is (from expression 9.1-3):

$$\int_0^{t_c} V_c(t) i(t) dt = \frac{1}{2} L i_L^2 + \frac{1}{2} V_o [i_o t_c + i_L t_o]$$

$$- \frac{1}{3} R [i_o^2 t_c + i_L (i_o + i_L) t_o] \quad 9.1-9$$

Fault Current Limited by Circuit

This case is essentially the same as the previous one except that the fault current is limited by the source impedance. The graphics are shown below:



The breaker operating time is determined by the source impedance. In the simple example just described, we can rewrite several equations (9.1-5 to 9.1-9).

The maximum fault current i_0 is given by:

$$i_0 = \frac{P}{Z \times V_0} \quad 9.1-10$$

where P is the rated capacity of the source and

$$Z = \frac{\% \text{ Impedance of the Source}}{100} \quad 9.1-11$$

Thus the expression for t_s is just:

$$t_s = \frac{i_0 - i_L}{V_0 / L} \quad 9.1-12$$

Now the current remains at i_0 until the countervoltage reaches system voltage, then it decays according to:

$$i = i_0 \left(1 - \frac{t - t_0}{t_c - t_0} \right) \quad 9.1-13$$

and the counter voltage is:

$$V_c = V_0 + \frac{L i_0}{t_c - t_0} \quad 9.1-14$$

The energy absorbed by the circuit breaker is:

$$\int_0^{t_c} V_c(t) i(t) dt = \frac{1}{2} L i_L^2 + \frac{1}{2} V_0 \left[i_0 (t_c + t_0 - t_s) + i_L t_s \right] \quad 9.1-15$$

$$- \frac{1}{3} R \left[i_L t_s (i_L + i_0) + 2 i_0^2 (t_0 - t_s) + i_0^2 t_c \right]$$