# A Hybrid Circuit Breaker Based on Current Commutation Approach for Multi Feeders DC Railway Substations

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***Abstract*— The paper presents an economic hybrid circuit breaker for limiting and interrupting the faults in DC railways substations. For fast fault current interruption, the hybrid breaker incorporates high speed mechanical contacts actuated by power semiconductor devices. Also, to avoid formation of electric arc, a commutation circuit is used to inject a counter current during fault interruption. On the other hand, in real railway substation, each feeder is connected to the main DC bus through an expensive air magnetic DC circuit breaker; and also connected to the auxiliary DC bus through another expensive one. This leads to high cost especially in railway substation, multi feeders are used to energize the vehicle transmission lines. The suggested breaker will replace all DC breakers in DC railway substation by a high speed mechanical contact with two semiconductor devices in each feeder besides only one commutation circuit to inject the counter current in all faulted feeders. The fault diagnosis is designed to detect the abnormal condition (current or voltage) in all feeders and direct the injected current from the commutation circuit to the faulted feeder only when the abnormal reached a predetermine level. The suggested breaker is able to detect and interrupt any cascading of faults.**

***Index Terms*— Arc-less circuit breaker operation, Fault current limiting and interruption, Hybrid DC circuit breaker, Railway Substation.**

## I. INTRODUCTION

DC distribution systems bring many advantages to the railway and industrial plants operation such as: greater levels of flexibility, redundancy and survivability [1]. In many DC railway substations and industrial plants short circuit current level has been the limiting factor for expanding or renewing these systems. In addition, advanced in DC railway technology and the ever increasing of its equipment's rating have led to more complex and powerful electric traction networks. It is consequently also more difficult to effectively design the circuit breakers, particularly where direct current is employed. Conventional DC circuit breakers force the current to decrease and extinguish it by means of an opposing arc voltage. Arc chute whose geometry and components are carefully designed is needed to obtain adequate reverse arc voltage [2].

The main problem associated with the DC circuit interruption is the absence of a natural current zero. Arc stretching and cooling techniques have been widely employed. The widely used air magnetic circuit breakers have suffered mainly from its breaking action, long fault clearing time, short life time, contacts wearing and high maintenance costs [3].

Alternative DC protection option is to use the solid state (static) circuit breakers. Static breakers have used power semiconductors switches to interrupt the fault current. In these breakers, the semiconductor switches such as thyristors or gate turn off thyristors (GTO) replace the mechanical contacts. Thyristor circuit breaker (TCB) based on the commutation principles can interrupt the fault current by either injection a counter current from a pre-charged capacitance source into the cathode terminal of thyristor devices or injection a counter current into the gate terminals of GTO devices. TCB has been successfully applied to protect DC railway substation. GTO circuit breakers produce very rapid current and therefore produce excessive over-voltages in practical systems. Static circuit breakers enable no moving parts, fast breaking action, arc-less interruption with high reliability and less maintenance. They are capable for interruption very high di/dt faults, and also capable for switching very high inductive loads. The static breakers suffer from excessive conduction losses; on-state voltage drop and a low let-through thermal withstand capability of the semiconductor devices [4].

Hybrid circuit breakers (HCB) based on current commutation approach have very fast moving mechanical contact in the main current path, a current zero is artificially created by superimposing a high frequency oscillatory current injected from a pre-charged commutation capacitor on the direct current to be interrupted [5]. Counter injected current from capacitive source, are similarly use to produce rapid extinction of electric arcs established between the contacts. HCB operates much faster than the conventional high speed air magnetic circuit breakers. Arcing is minimal and therefore maintenance is low. The conduction heat losses are extremely low, with consequent saving in energy and costs associated with cooling. HCB's have several interesting features: fast speed operation; limiting and interrupting faults; absence of a high electric arcs leads to lowered contact erosion, reduce noise and good repetition of operation [6].

## II. DC ELECTRIFIED RAILWAY SUBSTATIONS

The electrified railway substations are normally feed from two main high voltage three phases AC sources. One of them is the normal incoming and the other is the stand by incoming. Fig. 1 shown the Egyptian DC electrified railway network [7].

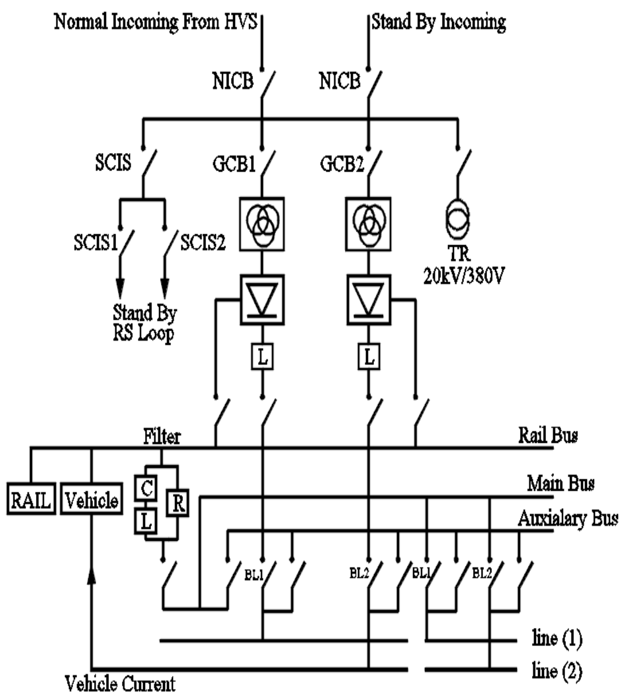



Fig. 1. Single Line Diagram for PI Railway Network

The normal incoming feeder contains four transformers (220/20 kV, 50 MVA) and the stand by incoming contains three transformers (66/20 kV, 50 MVA). Two tertiary power transformers (20/1.5 kV, 2.6 MVA) supplied two rectifier stations (1.25 MW, 1575 V, 750 A). The rectifier supplied two transmission lines (line 1 and line 2) through Rail bus, Main Bus, and Auxiliary Bus. Smoothing reactors 83mH, 2500A, and 1575 are used for smoothing the output DC supply. The auxiliary power transformer, in Fig. 1, (20 kV/ 380V) is used to feed the substation utilities, the control and protection circuits. Rail Bus represents the negative terminal of DC supply. Main Bus represents the positive terminal of DC supply. Auxiliary Bus represents the stand by positive terminal of DC supply. The Main Bus is normally energized, while the Auxiliary Bus is normally de-energized. Four air magnetic DC circuit breakers (BL1) are used to connect DC supply from the Main Bus or from the Auxiliary Bus to the transmission line1 through two feeders. The other four air magnetic DC circuit breakers (BL2) are used to connect the DC supply from the Main Bus or from the Auxiliary Bus to the transmission line 2 through other two feeders. The two standby RS loops are used to feed AC voltage to the next stations at failure of their sources [7]. Table 1 describes symbols meaning for PI railway network showing in Fig.1.

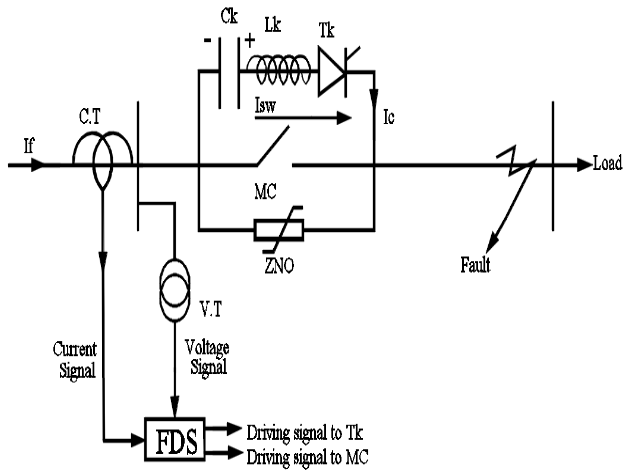
Eight magnetic air circuit breakers are using in the conventional protection to supply the DC voltage to the two transmission lines as shown in Fig. 1. A protection system known "Line Testing Device"; LTD; is used to check the magnitude of the source voltage; within the range of 1500 V; before closing the circuit breakers. Under and over voltage relay is used to open or prevent the circuit breaker from closing if the supply voltage decreased or increased the conventional value (1500 V) by 15%. In addition, another protection device called" Detector Device Line (DDL) which is actuated after the circuit breaker was closing its contacts. DDL is used to measure the rate of rise of the current, and when the measured value increased the pre-determine level will generate an open command to the circuit breaker. A thermal relay is used to protect the over load currents. There are also unit protection for each motor and transformer. A study for digital protection for Egyptian DC electrified railway network was discussed in [8].

TABLE 1
SYMBOLS MEANING FOR PI RAILWAY NETWORK

| | |
|---|---|
| NICB | Incoming Circuit Breaker |
| GCB1, GCB 2 | Group Circuit Breaker |
| SCIS | Stand By Cable Isolating Switch |
| L, C, R | Smoothing Reactor, Capacitor, and Resistor |
| BL1, BL2 | Magnetic Air DC Circuit Breaker |

## II. HCB BASIC IDEA AND EXPERIMENTS

The ultra-rapid HCB shown in Fig. 2 consist of a high-speed mechanical contacts (MC), a commutation circuit consists of solid-state switch Tk (IGCTs or SCRs), a pre-charged capacitor Ck; inductor Lk, fault diagnosis& control system (FDS), and varistor suppressor for energy path (ZNO). The HCB performs its duty by a combination of MC in the main current path and a proper counter current injection from the commutation circuit [9], [10]. During normal operation, MC is in closed position and thyristor Tk in a blocking state. Any fault occurring in the protected circuit is immediately detected by fault diagnosis system (FDS).

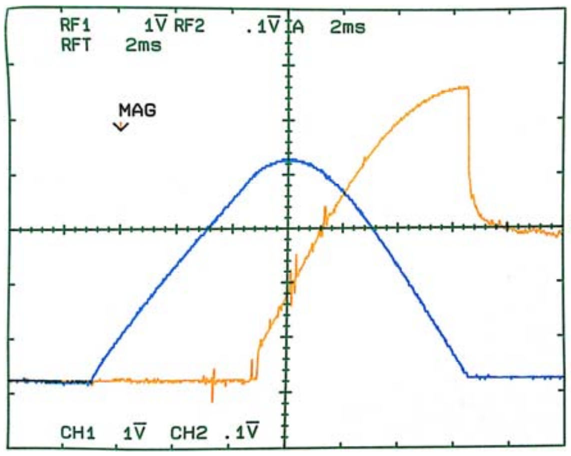



MC: Mechanical contacts, Tk: SCR, Ck: charged capacitor; Lk: inductor, FDS: fault diagnosis system, ZNO: varistor suppressor.

Fig. 2 HCB configuration for one Feeder.

One of the possible ways to get an arc-less circuit breaker is to introduce delay time to the transient recovery voltage TRV appearance. The selection of a proper delay time relates to the time needed for the final arc extinguishing. The basic concepts of HCB based on current commutation approach is to avoid the formation of electric arcs by counter current injection from the commutation circuit. The commutation approach is described whereby the current in the main circuit is brought to zero region by injection counter current from a pre charged capacitor. In HCB based on the commutation approach, fault current not stop following, it commutates the current from MC to commutation branch [11]. TRV starts to appear after a delay time interval depending on the time interval for discharging and charging commutation capacitor [12]. FDS operation will discuss later.

An industrial HCB model, rated 700 A at 1500 V DC was subjected to on-site short circuit tests. The commutation capacitor of 3 mF capacitance and initial charge voltage 325 V is used in series with a commutation inductor of 6 µH inductance. The waveforms taken at breaking fault current are shown in Fig. 3. Trace REF 1 represents the fault current of the HCB while trace REF 2 represents the recovery voltage. The maximum value for fault current has reached 3953 A (limited to less than 6 $I_{rated}$) and the maximum value for recovery voltage has reached 2760 V; TRV is limited to less than two times the supply voltage.




Vertical axis- Current (1000A/div); Voltage: (500V/div)
Horizontal axis for time (0.5ms/div)
REF1: Fault current REF2: Recovery voltage

Fig. 3 Experimental Waveforms for DC-HCB at Fault Current Interruption

## III. HCB Operation In Multi DC Feeder Railway Substation Protection

Interruption of DC fault current is more complex than interruption of similar AC. In real railway substation, each feeder is connected to the main DC bus through an expensive air magnetic DC circuit breaker; and also connected to the auxiliary DC bus through another expensive one. This leads to high cost especially in railway substation. Fig. 4 has shown DC voltage supply to line 1 and line 2 from the DC railway substation [7].

The circuit configuration for the suggested protection system for the four DC feeders of the railway substation indicated in Fig. 1; when supplied from the Main Bus is shown in Fig 5. Typical procedure is also used for the same four feeders when supplied from the Auxiliary Bus, not shown in Fig. 5. An ultra-fast mechanical contact (MC) is placed in each feeder. Two solid-state switches (IGCTs or SCRs) are used to connect each feeder with the commutation circuit. A Commutation circuit contains a pre-charged capacitor Ccom; and inductor Lcom is used to generate and inject a half wave capacitor current ($i_c$) through the MC. In addition, fault diagnosis and control system (FDS) is used to control all the semiconductor devices and all mechanical contacts. The operation of HCB for multi DC feeder's protection as follows:

Fig. 4. DC Substation Supplies Line 1 and Line2

During normal operation, all semiconductor devices in Fig. 5 are in blocking state and MC in each feeder is in closed position and supply DC power into line 1 & line 2 .

At fault conditions in any feeder, when the fault current ($i_f$) exceeds a discrimination level ($i_{dis}$) two opening command are simultaneously conveyed from the FDS; one to initialize the electro dynamic drive circuit to separate MC in the faulted feeder; the other opening command to turn-on the two semiconductor devices connected the faulted feeder to the commutation circuit. The electro dynamic driven circuit not shown in Fig. 5, generate a repulsion force that opening the MC in a fixed time interval about 100µs. Triggering the two semiconductor elements cause the commutation circuit to generate a half wave discharging current *($i_c$)* through the MC.

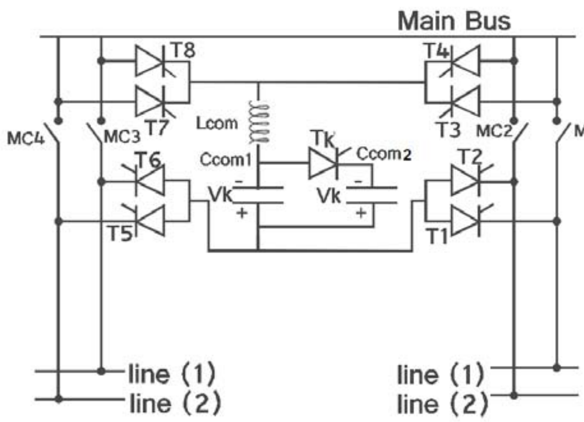



Fig.5. HCB Protection for Multi DC Feeders

### *A. Details of the HCB Breaking Sequence*

The counter current ($i_c$) is injected from the commutation circuit at the time instant when the fault current increased a predetermine level (($i_{dis}$). This injected current is passing through MC and opposite the fault current. After a definite time interval equal to the time interval for opening the MC; about 100 µs; the current ic has equal to the fault current $i_f$, the resultant current through MC is in zero region ($I_{MC}$= 0). A relatively small voltage appears across the MC as result of, zero current passing and, the on-state voltage of the semiconductor branch which is low. No electric arc appears during MC contacts separation. The Fault current starts to pass through the commutation circuit because the two semiconductor still in the on state condition. The commutation capacitor also, starts to charge in opposite polarity, the fault current and capacitor current decrease. At the time instant of complete charging of the commutation capacitor the two conduction semiconductor are turned off due to the reverse polarity of the commutation capacitor voltage. At this time instant the fault current with the capacitor current are forced to zero value; fault current complete interruption. The transient recovery voltage starts to appear across MC contacts. Therefore, a time lag interval before appearing the transient recovery voltage will prevent any re-ignition of electric arcs [13].

### *B. Simulation of HCB Operation in Railway Substation*

Operation of HCB when applied to protect DC feeders of railway substation has been simulated using a power full simulation package program named Piecewise Linear Electric Circuit Simulation (PLECS). The practical data for Egyptian DC electrified railway network given in section II, and shown in Fig 1, and Fig. 5 have been used for simulation. The feeder supplies the right section of line1 in Fig. 5 has subjected to short circuit at time instant 0.02 sec. The circuit configuration represents the faulted feeder is shown in Fig. 6. Simulation parameters of the circuit are given in table II.

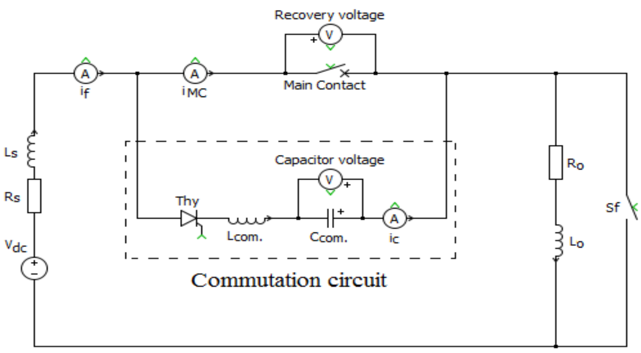



Fig. 6. Circuit Configuration Represents Faulted Feeder

TABLE II
Simulation Parameters for Circuit Configuration in Fig. 5

| Parameters | Symbol | Value | Unit |
|---|---|---|---|
| Source parameters | | | |
| Equivalent voltage | $E_s$ | 1500 | $V_{D.C}$ |
| Equivalent resistance | $R_s$ | 0.2 | Ω |
| Equivalent inductance | $L_s$ | 1e-3 | H |
| Load parameters | | | |
| Equivalent resistance | $R_o$ | 1.799 | Ω |
| Equivalent inductance | $L_o$ | 3e-3 | H |
| Commutation circuit parameters | | | |
| Commutation capacitance | $C_{com}$ | 0.95 | mF |
| Commutation inductance | $L_{com}$ | 6 | μH |
| Initial capacitor voltage | $V_{com}$ | 95 | V |

Fig. 7 has shown the rated current and the prospective short circuit current for the faulted feeder as simulated by PLECS. The prospective short circuit current; 7500 A; has reached more than ten times the normal rated current; 735 A. The simulated results in Fig. 7 nearly typical the actual practical data.

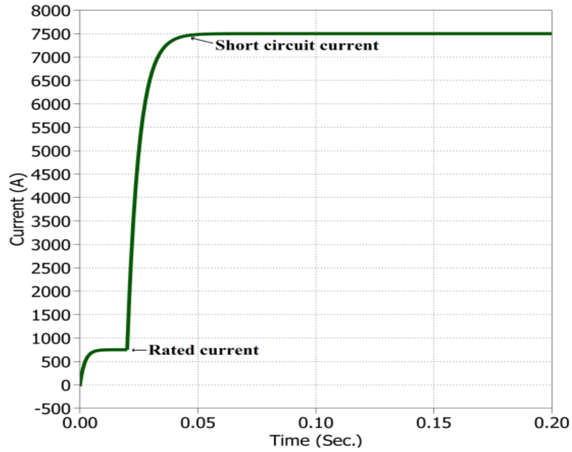
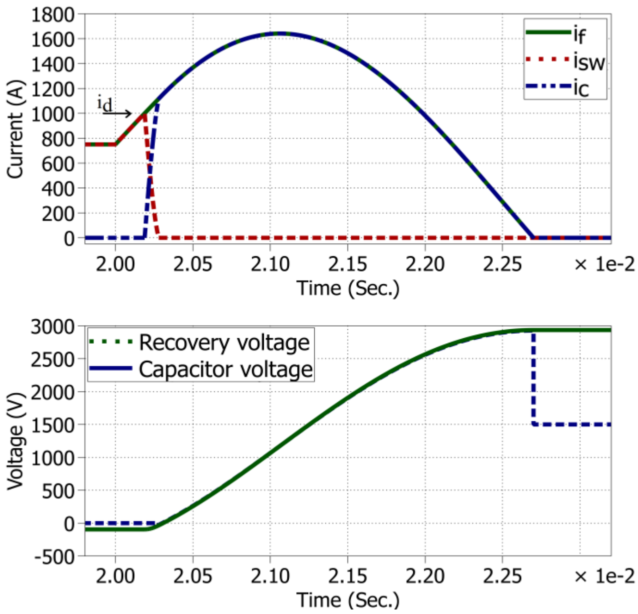



Fig. 7. Rated and Prospective Current Waveforms for Faulted Feeder

Fig. 8 has shown the fault current ($i_f$); the current through the main contacts MC ($i_{sw}$); and the injected current from the commutation capacitor ($i_c$); the recovery voltage across MC; and the voltage across the commutation capacitor when actuated HCB. The fault current and let- through current- has limited to 1600 A; fault clearing time for has limited to 270 μs; therefore, let trough energy has been reduced. The recovery voltage has delayed 200 μs before appearing across MC and the TRV has limited to 2910 V; less than twice the supply voltage.



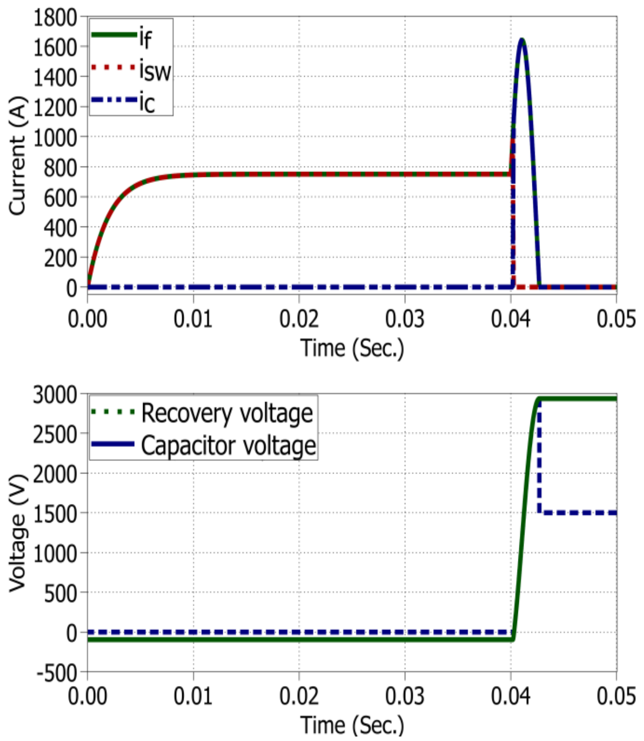

($i_f$): Fault current; ($i_{sw}$): Mechanical Contact MC Current; ($i_c$): Commutation Capacitor Discharge Current; ($i_d$): Discrimination Current
Fig.8. Current and Voltage Waveforms for Faulted Feeder

### *C. HCB Fault current Interruption*

From Fig. 8, the load current was 770 A, at the time instant 0.02 sec. a short circuit is happened in the feeder supply the right section of line 1 in Fig. 5. When the fault current reaches the discrimination value (1000 A); time instant 0.0202s; two open command signals from FDS were conveyed; one conveyed to the drive of MC and the other signal to thyristors in commutation circuit. The MC starts to separate its contacts and the capacitor current ($i_c$) injected from commutation circuit passes through MC; current through ($i_{sw}$) starts to decrease. This current is zero; $i_{sw} = 0$ when $i_c$ = if; contact separation interval 100 µsec. After opening MC, the fault current passes with the capacitor current through the commutation circuit; and charging the condenser $C_{com}$ to an opposite sign. The fault current is finally interrupted at the time instant 0.0226 due to the reverse polarity of voltage across semiconductors devices. TRV appears across the MC after delay time interval about 100 - 200 µsec. The TRV reaches maximum value about twice times the source voltage.

### D. *Cascading Fault Current Interruption Using HCB*

Other simulations have carried out using PLECS, where a short circuit has been occurred in the feeder supply the right section of line 2; after clearing first short circuit by 20 msec. the capacitor $C_{com2}$ shown in Fig. 5 is used to inject the counter current after triggering the commutation thyristor $T_k$. The resulting currents and voltages waveforms during current interruption process are shown in Fig. 9.




($i_f$): Fault current; ($i_{sw}$): Mechanical Contact MC Current; ($i_c$): Commutation Capacitor Discharge Current

Fig.9. Current and Voltage Waveforms during Cascading Short Circuit During Second Short circuit

## IV. Hybrid Circuit Breaker Design Consideration

The following issues have been investigated to develop a reliable HCB applied in multi feeder DC substations:

- *An* ultra-fast mechanical contact MC has to open its contacts in a time interval equal to the time interval that the counter injection current has equal current through MC; about 100 µs .
- HCB fault current interruption time must not exceed a millisecond; the butt contacts can be chosen [9]. These contacts are able to plastic deformation, kept in closed position by a clamp arrangement. The contacts can be opened by tear down due to the electro dynamic driven circuit. The success or failure of current interruption is determined by good arrangements between the electro dynamic driven circuit and the commutation circuit [13].
- The commutation circuit parameters $C_{com}$; $L_{com;}$ and the initial capacitor voltage $V_{com}$ have to select their values sufficient to generate the injection current with rate of rise able to reach the value of fault able to reach the value of fault current faster.
- The fault diagnosis and control system FDS has able to detect the faulted feeder and convey the opening command signals to the right semiconductor elements and the right MC.

## V. HCB Characteristics

- HCB can conduct the load current with a very small resistance in closing state and has an ultra-fast contact separation during faults.
- HCB has limit and interrupt the fault current at a current zero interval created by the counter injection current from the commutation circuit.
- HCB main contacts MC have to withstand the transient recovery voltage during interruption as well as the supply voltage.
- HCB has complete fault clearing and interrupted in a very low time; less than one second.

## VI. HCB Fault Diagnosis System (FDS)

HCB fault diagnosis system (FDS) comprises three stage of detection. The first stage has used to detect the short circuit using the amplitude comparator; the second stage has used to detect the let-through energy ($I^2t$) to protect system overload or thermal heat energy; the third stage has used to detect over/under voltage of the source. FDS is used to check the current and the voltage for each feeder in railway substation using the controller algorithm shown in Fig. 10.

In the first stage of the controller algorithm; the current signal from each feeder is compared with a certain constant level called discrimination current (about 1.5 – 2 of rated current) to decide if there is fault or not. The output signal from the comparator is supplied to an edge detection block which is used to actuate/not actuate S/R flop of the MC and S/R flop of the commutation circuit. At short circuit condition in any feeder the S/R flop of the main contact is actuated and has used to open MC of the faulted feeder; also S/R flop of the commutation circuit is also actuated and has used to trigger the two semiconductor devices which connected the faulted feeder to the commutation circuit.

The second part of the controller algorithm has been used for computation the let through energy ($I^2t$) to protect circuit overload and heat energy for the semiconductor devices. The current signal from each feeder is firstly squared and integrated over the fault clearing time period (1 ms) before comparing with a certain constant level equal $I^2t$ resulting from the load current (750A) in 1 msec. The output signal from the comparator is supplied to edge detection block which is used to actuate the S/R flop of the MC. At unequal conditions; the signal conveys from S/R flop is used only to open MC of the faulted feeder.

The third stage of the controller algorithm has been used for the over/under voltage detection. The voltage signal from each feeder is compared with a certain constant level for over voltage called discrimination over voltage ($V_{over}$ = 1750V) and also compared with other constant level for under voltage called discrimination under voltage ($V_{under}$= 1250V) to decide if there is over/under voltage or not. The output signal from the comparator is supplied to edge detection block which is used to actuate the S/R flop of the MC. At over/under voltage conditions the signal conveys from S/R flop is used only to open MC of faulted feeder.

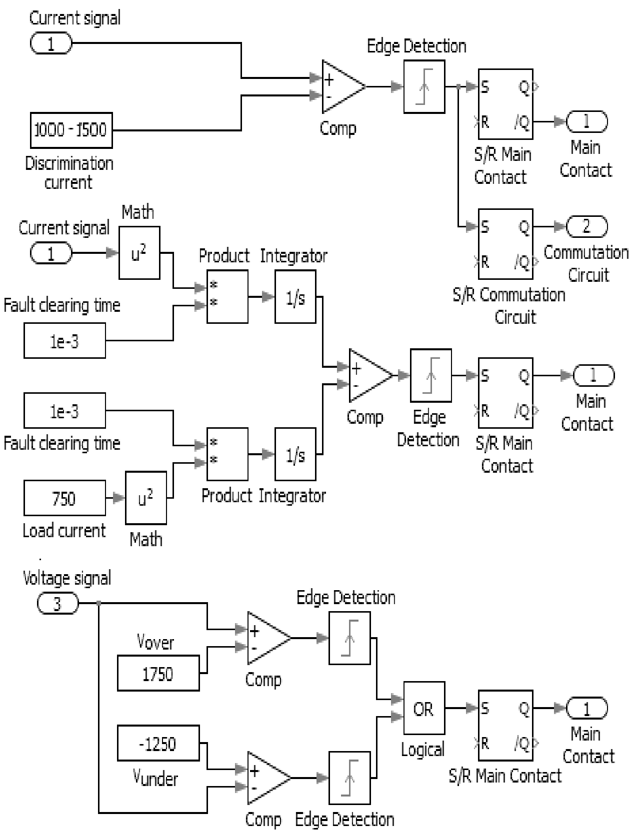



Fig.10. HCB Fault Diagnosis System

## VII. Conclusions

HCB would replace efficiency the magnetic air circuit breaker used inside railway substation. The results of the paper shows that the suggested HCB based on current commutation approach with one commutation circuit is more economic and prove suitability of using it for multi feeders DC railway substations protection. Moreover, the number of commutation condensers and their capacitance used for multi feeder protection have reduced at least to half value compared with applying a single pole for each feeder. Simulation tests have verified the reliability and capability to interrupt cascading faults in other feeders. The presented HCB is recommended for fast rising DC current interruption. HCB has the potential to realize the function of the protection device as the current limiter and interruption because its ability to reduce the let-through current; reduce the let-through energy; delay the recovery voltage and forced the fault current to zero.

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