Abstract—A new type of DC breaker, based on standard SF$_6$ AC circuit breakers with auxiliary circuits will now be used in the Three Gorges-Changzhou HVDC Project instead of the old type based on oil-minimum breakers. To create the current zero necessary for arc extinction, a passive auxiliary circuit is used for lower currents, and an active circuit at higher currents. The passive circuit comprises a capacitor in series with a reactor, and a parallel non-linear resistor, across the breaker; in the active circuit the capacitor is precharged and inserted at a suitable time. The paper describes theoretical models and testing of the new breakers, and how they are implemented in reality.

Index Terms--Bipolar transmission, DC Breaker, GRTS, HVDC, Metallic return, MRTB, Multi-terminal schemes, NBGS, NBS, SF$_6$ breaker, Transient analysis.

I. INTRODUCTION

DC switches are used in bipolar HVDC schemes for different purposes: To reroute the DC current during reconfiguration of the main circuit, and to help extinguish fault currents. An important example is the Metallic Return Transfer Breaker (MRTB), which is used for commutating the current from the ground path to a metal conductor, when there are restrictions on how long time a DC current through the ground can be allowed. Other examples are Ground Return Transfer Switch (GRTS), Neutral Bus Switch (NBS) and Neutral Bus Grounding Switch (NBGS), Fig. 10. Future applications may include DC switches on the high potential side in multi-terminal schemes. The purpose of this paper is to show how the old type of DC switches based on oil-minimum breakers is now replaced by a new type based on standard SF$_6$ breakers.

II. COMMUTATION PRINCIPLE

The principle is shown in Fig. 1. Before $t = 0$, the circuit breaker CB is closed and the total current $I$ is assumed to be distributed by $R_1$ and $R_2$ as $i_1(0)$ and $i_2(0) = I - i_1(0)$ in steady state. To commutate the current $i_1(0)$ in branch R1-L1 (e. g. ground return) to branch R2-L2 (e.g. metallic return), CB is opened and a counter-voltage $U$ is established (details below). With the simplified assumption that $I$, $U$, $L_1$, $L_2$, $R_1$ and $R_2$ are constant, an exponential solution is obtained for $i_1(t)$ with a time constant $\tau = (L_1 + L_2)/(R_1 + R_2)$, and the commutation time $t_k$ and energy $W$ to be absorbed (in a non-linear resistor, explained below) are

$$t_k = -\tau \cdot \ln \left( 1 - i_1(0) \cdot \frac{R_1 + R_2}{U} \right)$$  \hspace{1cm} (1)$$

$$W = U \cdot i_1(0) \cdot (t_k + \tau) - t_k \cdot U^2 / (R_1 + R_2)$$ \hspace{1cm} (2)$$

In reality, inductance and resistance are frequency dependent (especially when the ground is involved), but if values for a characteristic frequency are used, (1) and (2) can be useful for approximate calculations.

![Fig. 1. Commutation of a current from branch R1-L1 to R2-L2 by means of a counter-voltage U, principle.](image)

Passive and Active DC Breakers in the Three Gorges-Changzhou HVDC Project

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In the passive circuit, a capacitor in series with an inductor is connected in parallel with the SF$_6$ circuit breaker, Fig. 2. This circuit is under certain conditions unstable, and an oscillation starts to grow until current zeros are created where the arc can be extinguished as in a conventional AC breaker. Instead, a current zero must be created. For a long time, oil-minimum breakers with a parallel circuit comprising a spark gap in series with a capacitor have been used (Fig. 2). Since oil-minimum breakers have several disadvantages, this type of breaker is now being replaced by standard SF$_6$ breakers. However, SF$_6$ breakers need a different auxiliary circuit due to their lower arc voltage. Two types of auxiliary circuits are presently used, passive and active.

III. PASSIVE DC CIRCUIT BREAKERS

In the passive circuit, a capacitor in series with an inductor is connected in parallel with the SF$_6$ circuit breaker, Fig. 2. This circuit is under certain conditions unstable, and an oscillation starts to grow until current zeros are created where the arc can be extinguished. When the arc is extinguished, the capacitor is rapidly charged until the non-linear resistor takes over the current and limits the voltage to a suitable value. The energy $W$ (2) is deposited in the resistor.
A. Theoretical Models and Simulations

It is well known that the current through an electric arc with a parallel capacitance (Fig. 2) can start to oscillate if the arc characteristic has a negative derivative dU/dI (Fig. 3). This can lead to unintended current chopping in AC applications [1], [2], but it can also be used to interrupt DC currents.

Small deviations from a static point P1 (Fig. 3) can be described by an equivalent circuit [1], Fig. 3, where also the external capacitor and inductor from Fig. 2 are included. At high frequency the arc behaves like a resistor, which means that the circuit becomes unstable, will grow as

\[ Z(j\omega) = \frac{1}{(\alpha + j\beta)} \]

which means that the circuit is unstable below this limit, and stable above. In the more general case, where the characteristic locally is given by \( R_a \) and \( U' \), numerical methods are needed to find the limit.

In general, the arc parameters \( R_a \), \( U' \) and \( \theta \) must be inferred from tests, and \( \theta \) is perhaps the most difficult one to determine. However, if it is obvious that a circuit as in Fig. 2 under test is close to the instability limit, the real part of \( Z(j\omega) \) is close to zero, and this simplifies the calculation of \( \theta \). With such methods, the arc parameters can be determined for different arc lengths and blast pressures in a circuit breaker.

With a model calibrated in this way, further testing can be made more efficient. In the model, as in reality, the instability limit will be time-dependent as the arc parameters change with the arc length and the blast pressure. This means that for a constant current, the circuit may first be stable, and then become unstable at a certain time when the breaker opens.

Putting the real and imaginary parts of \( Z(j\omega) \) equal to zero gives a natural frequency and an instability limit. As an example, if the arc characteristic is given by \( U/I = \beta \) (a reasonable approximation at lower currents), the instability limit is given by the well-known expression [1], [2]

\[ I_{inst} = (\beta \theta C / \theta^2 - \alpha LC)^{1/(\alpha + 1)} \]

where \( L \) and \( R \) can be determined from (3). Interruption will take place when \( i \) has grown to the DC current through the breaker. The model shows that there is an optimum value of the inductance in the circuit which gives the shortest interruption time. However, when the inductance is increased, instability sets in earlier until the circuit becomes unstable at all. Low inductance gives late instability, and thus long total interruption time. When the inductance is increased further, the growth rate decreases (4), and the interruption time becomes longer again.

Simulations have also been made with a black-box model, [3]:

\[ dG/dt = (G_s - G)/\theta \]

where \( G_s \) is the stationary arc conductance (Fig. 3), \( G \) the

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Fig. 2. **Left:** Oil-minimum breaker with auxiliary circuit including a spark gap. **Right:** SF6 breaker with a passive auxiliary circuit, explained in text.

Fig. 3. Static arc characteristic (left), and equivalent circuit for arc, together with an auxiliary circuit (right).
actual, momentary value of $I/U$, and $\theta$ the time constant of the arc. As is seen, under steady state conditions $G = G_s$, but if $G$ differs from $G_s$, $G$ will approach $G_s$ at a rate determined by the arc constant. $G_s$ and the time “constant” $\theta$ are functions of arc length and blast pressure (and thus of time) and have been calibrated against tests. If (5) is coupled with the differential equation for the auxiliary circuit, Fig. 2, the interruption process can be simulated. An example is shown in Fig. 4, where a successful interruption of 1.1 kA is simulated with an auxiliary circuit where $C = 9 \mu F$ and $L = 30 \mu H$.

The maximum current that could be interrupted with this breaker was 2.5 kA, indicating that point P2, where $dU/dI = 0$, Fig. 3, had been reached, and arc characteristics plotted from current and voltage data from all tests supported this view. Interruption of higher currents with a passive circuit requires a specially modified breaker chamber to move P2 in Fig. 3 to a higher current. However, ABB Power System prefers to use standard, well-proven components, and instead an active auxiliary circuit, described below, will be used for higher currents.

B. Tests

In parallel with the theoretical investigations, tests have been done. The purpose has been both to calibrate the models, and to test the performance limits of the different circuits. A standard, one-chamber, AC SF$_6$ puffer breaker of type HPL 245 B1 was tested with a passive circuit with different values of capacitance and inductance, and the current was varied to find the instability and interruption limit. The capacitance was chosen to give a high instability limit and an acceptable derivative of the recovery voltage at an acceptable cost. When the inductance was varied, an optimum was found which gave the shortest interruption time as in the model described above. In these tests the total inductance in the auxiliary circuit was measured separately. The minimum inductance without any reactor in the auxiliary circuit, i.e. the stray inductance, was determined to 30 $\mu H$ in the test setup. An example of a test oscillogram is shown in Fig. 5.

Theoretical models and simulations have been compared with, and supported the tests in several ways. As a check of self-consistency, the predicted instability limit versus parallel capacitance with a stray inductance of 10 $\mu H$ and 20 $\mu H$, and test results.

C. Comparison between calculations and tests

Fig. 6. Comparison between theoretically calculated instability limit versus parallel capacitance with a stray inductance of 10 $\mu H$ and 20 $\mu H$, and test results.

Fig. 5. Example of a test oscillogram showing interruption of 2.5 kA. Arc (and recovery) voltage $U_{ARC}$, arc current $I_{TB}$ (with unintended low-frequency ripple from the feeding circuit), contact separation TRAVEL and puffer pressure PRESS versus time. The recovery voltage is limited after interruption to 34 kV by a non-linear resistor.
model has been used to predict the instability limit, assuming a small (stray) inductance. As is seen in Fig. 6, 10 µH gives a limit that is too low, whereas 20 µH gives a reasonable agreement with the tests (later measurements in a similar test circuit gave a stray inductance of 30 µH).

The simulations have also showed good agreement with test results and made it possible to find limits with fewer tests than otherwise would have been possible.

IV. ACTIVE DC CIRCUIT BREAKERS

When the DC current is above the instability limit, an active circuit is needed to create current zeros. Several methods are possible, but the simplest one is to insert a precharged capacitor into the auxiliary circuit, Fig. 7, when arc length and blast pressure in the SF₆ breaker are sufficient [4].

A. Simulations

The same calibrated black-box model as for the passive circuit, but with a "switch" for insertion of the charged capacitor has been used. An example is shown in Fig. 8, where interruption fails in the first two current zeros, but is successful in the third. Simulations with different charging voltages and different polarities have been done. If the voltage is too low, interruption will as expected fail, but opposite polarity is no problem.

Fig. 7. An SF₆ breaker with an active auxiliary circuit with charging device and a non-linear resistor.

Fig. 8. Example of a simulation of a successful interruption of 5 kA with an active circuit with C = 18 µF charged to 15 kV and L = 100 µH.

1) Tests

A standard, one-chamber, AC SF₆ puffer breaker of type HPL 245 B1 was tested with an active auxiliary circuit where the charging voltage and polarity were varied. Successful interruptions were achieved with both polarities up to 5 kA; higher currents were not tested. An example is shown in Fig. 9. In general, good agreement was found between the simulations and the tests, as Fig. 8 and Fig. 9 illustrate.

V. DIELECTRIC TESTS

In the tests with passive and active circuits (Fig. 5 and Fig. 9), the recovery voltage was limited to 34 kV, which was enough to successfully demonstrate the thermal part of the interruption and a part of the dielectric recovery. However, in a real application a much higher voltage is needed (of the order of 100 kV for an MRTB). In the laboratory, such a high recovery voltage can only be obtained in a synthetic circuit, where the relevant DC current through the breaker is interrupted, followed by a realistic recovery voltage injected from a separate circuit. Such tests have shown that the breaker can withstand at least 126 kV after having interrupted 4 kA.

VI. COMMUTATION IN A REAL NETWORK

Although simple equations as (1) and (2) can give valuable information, the final rating of the DC breaker components in a real application requires a transient analysis. The frequency dependence of the inductance and resistance must be taken into account, especially for the ground. The frequency range of interest here is from below 0.01 Hz up to tens of Hz. Since this range is below what standard line models in commercial simulation programs can handle, special models had to be developed. Data for overhead lines and earth resistivity gives, together with the Carson equation for the equivalent current depth, series impedance and shunt admittance matrices for different frequencies. From these matrices, pole and ground mode impedances needed in the model can be calculated. For the ground path, a model comprising series connected links,

Fig. 10. The commutation circuit for the MRTB (before opening).

each containing a number of parallel branches of an inductance and a resistance in series, is used. Using special software, the component values are selected so that the frequency dependence of the impedances in the model
correspond to the impedances calculated above. As an example, Fig. 10 shows a case where the current is to be commutated from ground to metallic return by the MRTB, and Fig. 11 shows the corresponding EMTDC simulation model.

VII. DESIGN OF DC SWITCHES

In a practical design, there are many additional considerations of importance. The auxiliary circuit must be placed on an insulated platform, and the active circuit also needs a charging device, Fig. 12. Furthermore, for the MRTB and the GRTS, the non-linear resistors must be rated for more than one commutation, and the sequence control must be able to reclose in time if the commutation fails.

VIII. DISCUSSION

Since the present design was developed and tested with the Three Gorges-Changzhou Project in mind, higher currents and voltages were not tested; however, all tests were successful, and thus there is a potential for still higher performance. Inspection after many tests also showed very little wear of the breaker chamber. Future applications may also include the high-potential side, possibly with multi-chamber breakers.

Alternative designs were of course considered, e. g. a modified breaker chamber for use with a passive circuit at higher currents, but such development is very costly and it is questionable if 5 kA can be reached at all, cf. [4]. Therefore, ABB prefers to use standard SF₆ breakers. Semiconductor alternatives were also discussed, but at the present they are not competitive, although the situation may change in the future.

IX. CONCLUSION

In the Three Gorges-Changzhou HVDC Project, DC breakers are being constructed according to the principles described above. The new DC breakers have many advantages over the previous oil-minimum type, and there is still a potential for further development.

X. REFERENCES


XI. BIOGRAPHIES

Dag Andersson was born in 1942, and graduated from the Royal Institute of Technology in Stockholm, where he later got a doctor's degree in electron physics. His research experience includes plasma and arc physics, and he has been a visiting scientist at the European Space Agency. His present field of activity at ABB Power Systems includes electromagnetic compatibility and related problems in connection with HVDC.