A Guide to the DC Decay of Fault Current and X/R Ratios

Introduction
This guide presents a guide to the theory of DC decay of fault currents and X/R ratios and the calculation of these values in Ipsa.

Many methods of calculating DC decay and X/R ratios exist, both in the form of IEC and ANSI standards as well as the implementations used in power system analysis packages such as Ipsa.

This guide aims to present a brief overview of the theory in order that the calculation methods can be understood and correctly applied.

The results of validation studies are also presented to demonstrate that the techniques applied are accurate. Recent investigations have identified the requirements for improvements in the calculation of the DC currents and X/R ratios, the results of these are presented and explained.

Theory
The Decay of DC Fault Current
It is not possible to instantly change the currents flowing through the system inductances; therefore any fault results in a transient DC current being produced. The resulting fault current, either from a generator, through the system or into the fault is shown below;

The DC current is shown as the black line decaying from an initial current of 0.5kA to approximately 0.1kA.
DC Decay of Fault Currents and X/R Ratios

For a simple system comprising a resistance and reactance this decay is exponential and can be calculated using the well known formula as follows:

\[ I_{DC} = \sqrt{2}I''_K e^{-2\pi f t \frac{R}{X}} \]

Where:
- \( I_{DC} \) = DC current at time \( t \)
- \( I''_K \) = Initial RMS (symmetrical) current
- \( f \) = System frequency (Hz)
- \( t \) = Time after fault inception (seconds)
- \( R \) = System resistance (ohms or per unit)
- \( X \) = System reactance (ohms or per unit)

This formula contains the term \( R/X \) which is more commonly expressed in its inverse form as the X/R ratio.

The ratio of the resistance to reactance therefore determines the length of time taken for the DC current to decay to a particular value. The X/R ratio is therefore often used in the rating of circuit breakers and switchgear as it determines the quantity of DC current that the system must withstand or interrupt.

In the case of a fault at the terminals of a single generator the stator resistance \( R_s \) and sub-transient reactance \( X''_d \) are used in the above formula.

If the fault occurs remotely from the generator terminals then the X/R ratio must also take into account the impedance of any cables, lines and transformers etc between the generator and the fault location. The X/R ratio therefore changes with the fault location.

It is important at this stage to understand the relationship between the X/R ratio, the generator impedances and the decay of the DC current;

- The generator sub-transient, transient and synchronous reactances \( (X''_d, X'_d, X_d) \), and associated time constants \( (T''_d, T'_d) \), are determined at the design stage or from generator testing.
  - These reactances and time constants are typically determined from a fault current curve; that is the reactances are selected to give the fault currents observed during testing.
  - These reactances are effectively fictitious values designed to replicate the behaviour of the real generator
- The decay of the DC current is represented as the change from the sub-transient to transient and finally to synchronous reactance over a certain time.
  - This is represented using a single exponential decay, the time constant of which is given by the resistance and sub-transient reactance, or X/R ratio
  - The X/R ratio is therefore a measure of the DC decay of the generator
- The X/R ratio provides an approximation of the DC decay
  - It is calculated from the actual DC current, the DC current is not calculated from the X/R ratio.
For systems with multiple generators the determination of the X/R ratio is more complicated. The figure below shows the DC currents for a system with two generators:

The two generators have both different DC fault currents and different rates of decay, or X/R ratio. When these two currents summate at some point in the network they do not result in a current with a single exponential decay. Instead the summated current needs to be represented as the sum of two exponentials. The graph below shows how the two summated generator currents cannot be exactly represented using a single exponential curve, shown as dotted lines.

As shown above the X/R ratio does not provide an accurate method of determining the DC current at any particular time. For fault times of 20ms and less the X/R ratio is approximately 6 but this increases to a ratio of 9 for fault times of 100ms.

It is therefore important to note that the X/R ratio is not a precise value. Instead it is an approximation of the exact DC current decay at a particular location and at a particular time after the fault.
**Ipsa Modelling**

The fault calculations in Ipsa always calculate the DC current for each individual generator at a particular fault time. These individual DC currents are based on the generator sub-transient reactances and time constants as well as the impedance between the generator and the fault point. This gives the most accurate calculation of the DC current for each generator.

The fault calculation then summates these individual currents to provide the total fault current, branch flows etc.

The X/R ratio at the point of fault is then calculated from the resulting fault current from all generators. Ipsa provides two methods of calculating the X/R ratio, these are described below.

**Driving Point Method**

The driving point method calculates the X/R ratio at the instant of the fault, i.e. zero milliseconds. The total DC fault current at the fault location is first determined from the individual generator contributions.

The total DC current is then represented as a voltage behind an equivalent impedance, the impedance being chosen to give the calculated fault current. The X/R ratio is then obtained directly from the value of this equivalent impedance.

This provides a single fixed X/R ratio at the fault point. As the X/R ratio is calculated at the initial fault time it is only valid at that time. Therefore Ipsa only provides the X/R ratio at zero milliseconds for the driving point method.

This is illustrated in the graph below. The total fault current at zero milliseconds for “Gen 1 + Gen 2” is used to determine the X/R ratio. This results in an under-estimate of the X/R ratio at fault times of approximately 20 milliseconds and above.
DC Decay Method
The DC decay method provides a more accurate calculation of the X/R ratio as it changes the ratio with the fault time.

For this calculation Ipsa determines the DC fault current at both zero milliseconds and at the fault time requested by the user, e.g. 100 milliseconds. These two DC fault current values are then used to determine the X/R ratio. This is achieved by calculating the X/R ratio which gives the correct DC current at 100 milliseconds given the initial DC current.

This is shown in the figure below;

The total fault current at zero milliseconds and 100 milliseconds for “Gen 1 + Gen 2” is used to determine the X/R ratio. This results in an X/R ratio which gives the correct DC fault current at the required fault time. It should be noted that the X/R ratio is only valid at the fault time that it has been calculated for. In the example above the X/R ratio would give a higher DC current than Ipsa for fault times between approximately zero and 90 milliseconds.
Validation Studies
The correct calculation of the X/R ratio for a system with multiple fault current sources is complicated and, as shown above, can give significantly different results at different fault times. In order to overcome some of the difficulties of the X/R ratio calculation the two methods presented above were developed and implemented in Ipsa.

The DC Decay method was developed specifically to provide a more accurate X/R ratio result at typical fault break times, when the remnant DC current is important in the rating of circuit breakers.

To determine if the methods applied in Ipsa are correct validation studies are undertaken using software such as PSCAD. PSCAD is an electromagnetic analysis tool which models the generator and power system components in a higher level of detail than Ipsa. It is typically used for very fast transient studies such as insulation coordination and over voltage studies.

The following test system was modelled in both Ipsa and PSCAD. It represents a remote 400kV generator and a local 132kV generator. Two transformers are included, one between the generators and one to a 33kV busbar where the fault is applied. This network was chosen for validation studies as it exhibited specific characteristics which highlighted some inaccuracies in the Ipsa 2.3.1 calculations. These concerned the influence of a small local generator on the fault current from a large but electrically remote generator and visa versa.
Ipsa 2.3.1 Studies

The following graphs detail the PSCAD and Ipsa results for the above network using Ipsa 2.3.1. In Ipsa they were obtained by performing a waveform plot for a fault at the 33kV busbar.

For this network it can be seen that the DC component of the Ipsa fault current does not decay as quickly as the PSCAD results. Note that the DC current is not directly available in PSCAD and therefore the full AC waveforms have been shown for both Ipsa and PSCAD.

The X/R ratio of the DC current above is reported by Ipsa as follows:

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>Calculation (Fault) Time</th>
<th>Ipsa 2.3.1 X/R Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Point</td>
<td>0 ms</td>
<td>21.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>0 ms</td>
<td>33.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>200 ms</td>
<td>38.1</td>
</tr>
</tbody>
</table>

It is clear that the X/R ratio calculated by the two methods is significantly different.
Ipsa 2.3.2 Studies

Enhancements to the calculation of the DC current have been made in Ipsa 2.3.2 in order to provide a more accurate representation of the decay. The following graph shows the comparison between Ipsa 2.3.2 and PSCAD;

The enhancements have resulted in a more accurate DC decay when compared to the reference model in PSCAD. The following table summarises the X/R ratios calculated by Ipsa 2.3.2;

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>Calculation (Fault) Time</th>
<th>Ipsa 2.3.2 X/R Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Point</td>
<td>0 ms</td>
<td>21.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>0 ms</td>
<td>24.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>200 ms</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The above table shows that the method added to Ipsa 2.3.2 provides more accurate values for the X/R ratio for the DC Decay method. The values reported for the driving point method do not change as they are only available for a fault time of 0ms. The DC Decay method also demonstrates that the X/R ratio decreases slightly with fault time and converges towards the value given by the driving point method.
Ipsa 2.3.1 and 2.3.2 Comparison
The following graph provides a comparison between the Ipsa 2.3.1 and 2.3.2 calculations;

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>Calculation (Fault) Time</th>
<th>Ipsa 2.3.1 X/R Ratio</th>
<th>Ipsa 2.3.2 X/R Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Point</td>
<td>0 ms</td>
<td>21.6</td>
<td>21.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>0 ms</td>
<td>33.6</td>
<td>24.6</td>
</tr>
<tr>
<td>DC Decay</td>
<td>200 ms</td>
<td>38.1</td>
<td>21.8</td>
</tr>
</tbody>
</table>
Summary
An enhanced DC decay calculation method has been introduced in Ipsa 2.3.2 which improves the representation of DC fault currents. This option is available by checking the “Use enhanced synchronous machine modelling” option in the fault analysis dialog shown below. This option is used for both the driving point and DC decay calculation methods.