The simulation of A. C. voltage levels for line-to-ground faults at the A. C. bus-bar of an HVDC inverter.

John H. Hobson

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THE SIMULATION OF A. C. VOLTAGE LEVELS
FOR LINE-TO-GROUND FAULTS
AT THE A. C. BUS-BAR OF AN HVDC INVERTER

by

John H. Hobson

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12/5/77
(Date)

Professor in Charge

Chairman of Department
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THE SIMULATION OF A. C. VOLTAGE LEVELS
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ABSTRACT

Even though high voltage direct current (HVDC) links have been in commercial use for over twenty years, very little is known about how the voltage level at an inverter behaves during a.c. faulted conditions. It is well known that any fault or unbalanced load in an a.c. system could cause instability. But how does the inverter behave to this condition?

The severe unbalanced loading of an HVDC inverter system can cause abnormal operations within the inverter. The most common abnormal operation is the failure to commutate from one valve to the next. This can be caused by three conditions: a delay in firing time; a voltage imbalance between two phases; or an increase in direct current while holding a constant firing angle.

Why is a commutation failure of importance? The most frequent abnormal inverter operation is commutation failure. During a commutation failure a short circuit occurs in the bridge, during which no power is transferred to the a.c. network. This, combined with the voltage imbalance in the a.c. system, may cause instability. A better understanding of what occurs during commutation failure and its effects on a.c. network will enable us to develop methods to minimize these effects.

This thesis presents the several relationships between vari-
ous quantities for the case of a single phase fault on an inverter output. Included are a rigorous mathematical determination of the minimum value of voltage of the faulted phase before commutation failure occurs as a function of the firing angle and graphical presentations showing the variation in the line voltage and a.c. output current for differing fault impedances. The data presented is that generated by numeric solution of a state variable model of a twelve pulse inverter. Solutions are presented for two cases of constant current and constant voltage supplied from the d.c. source.

Six simulations were made for each case, one without a fault and the other five with different values of fault impedance. This data was used to derive the relationships between the line voltage of the faulted phase and the impedance of the fault; also between the a.c. line current on the faulted phase and the impedance of the fault. It was discovered that the per unit value of the voltage had the relationship of \( \frac{L_f}{L_f + X_C} \) with the fault impedance. The current was related to the fault impedance by the relationship \( \frac{b}{L_f + X_b} \). One simulation was made where the fault was removed after five cycles and from this it was discovered that the bridge did not recover. For the above relationships \( L_f \) is the fault inductance, \( X_C \) and \( X_b \) are the break points in the curves and \( b \) is the gain factor for the last relationship.
INTRODUCTION

The first commercial high voltage direct current (h.v.d.c.) transmission line was put into operation in 1954. This was the Gotland link which ties Gotland Island with Sweden. In the two decades since the Gotland link went into operation many technical advances have been made. One was the development of the solid state silicon controlled rectifier (SCR). These SCR's, which are also called thyrists, are used now in many converter bridges instead of the mercury vapor valves. Another development was the sophisticated control systems which became available with the development of solid state devices. These advances of technology are a factor which helps to reduce the cost of d.c. line to a.c. line termination. This termination is the most costly part of the h.v.d.c. links and today d.c. links are economically competitive with a.c. lines in many cases.

D.c. lines are used mainly for two purposes in present systems: as an asynchronous link between two a.c. systems and to aid in the stability of an a.c. network. The asynchronous link gives two power networks the ability to exchange energy without the requirement that they be synchronized. Also, a disturbance in one system would not tend to be transmitted to the other. In the second case the d.c. link is embedded in an a.c. network to enhance the stability of the network. This comes from the fact that the d.c. link responds much faster to a change in transmitted power than an a.c. line. When h.v.d.c. circuit breakers become economically feasible, the development of h.v.d.c. networks will become possible. These networks will
allow power pools to transfer energy without the possibility of changing the stability of their systems.

There are five types of h.v.d.c. converter abnormal operations: backfire, arcthrough, quenching, misfire, and commutation failure. Backfiring is when a valve conducts current in the reverse direction. Archthrough, or shoot thru, is when a valve conducts during a period in which it is scheduled to be blocking. Quenching is the condition when the current is prematurely extinguished. A misfire is when the valve fails to conduct when it is “turned on”. Commutation failure is when the commutating emf reverses before commutation is completed; this case occurs only in bridges operating in the inverter mode. The first four abnormal conditions are misoperations of the individual valves and independent of the a.c. and d.c. systems. But the last one is a misoperation of the entire bridge and is brought about by unbalanced loading of the a.c. system.

This paper will investigate the effects of line-to-ground faults with different values of fault impedance on the operation of a twelve pulse inverter. In this case the most frequent misoperation is commutation failure. First a relationship for the determination of the minimum line voltage which ensures normal operation is derived. Then a relationship between the line voltage and the fault inductance is determined from the simulation data (it is assumed that the fault impedance is purely inductive). Also, a relationship between the current supplied by the a.c. system to the fault and the fault inductance is determined. But let us start with an explanation of commutation and commutation failure.
What is commutation? It is the process of reducing the current in one valve and increasing it in another. This is done by the following process:

\[ i_{\text{r1}} = i_{\text{dc}} - i_c \]  
\[ i_{\text{r2}} = i_c \]  
\[ \frac{di}{dt} = \frac{(V - V_1)}{2L} \]  

Equation (3) is valid until \( i_c = 0 \). Then valve no. 1 ceases to conduct and \( i_{\text{r2}} = i_{\text{dc}} \). The commutation time is the time it takes for \( i_{\text{r1}} \) to go from \( i_{\text{dc}} \) to zero. This time rate of current change varies directly with the commutation emf \( (V_2 - V_1) \).
What is commutation failure? It is the condition when the current fails to commutate from one valve to the next. This will occur if the commutation emf changes polarity before the end of the commutation period. If this does happen then the current transfers back to equal $i_{dc}$ in the valve which was to be blocked.

Some common conditions which will cause a commutation failure are: a delay in the firing time, a change in the voltage in one or two phases, and an increase in direct current with the firing angle held constant. Many commutation failures are caused by voltage drops due to faults in the A.C. systems.

The following is a derivation of a relationship between voltage level (which will cause commutation failure) vs. the firing angle. First we define the commutation emf as the voltage between the two phases which are commutating. Next we assume that the voltage $V_1$ is reduced by a factor of "a"; but with no change in phase, and that voltages $V_2$ and $V_3$ retain their original magnitude but are shifted in phase. (See Figure 2).
\[ V_1 = a \, E_m \cos (\omega t + \pi/3) \]  
\[ V_2 = E_m \cos (\omega t - \pi/3 + \epsilon) \]  
\[ V_3 = E_m \cos (\omega t - \pi - \epsilon) \]  
\[ \text{such that } V_1 + V_2 + V_3 = 0 \]

(4a)  
(4b)  
(4c)  
(5)

Now substituting equation (4c) into equation (5) gives the relationship between \( a \) and \( \epsilon \).

\[ 0 = a - 2 \cos (\epsilon + \pi/3) \]  
\[ \epsilon = \cos^{-1} ((a \cdot 2) - \pi/3) \]  
\[ a \text{ is the firing angle} \]  
\[ \delta \text{ is the extinction angle} \]  
(6)  
(7)
In referring back to equation (3) we get equation (8)

$$ l_d = l_r = \frac{V_m}{2\omega L_c} \int_0^\theta \cos (\theta - \pi/3 + \xi) - a \cos (\theta + \pi/3) d\theta $$

(8)

Where $\theta = \omega t$

Now $\xi$ is chosen as the angle at which the commutation emf is zero.

By using the relationships given in equations (9) and (10 a-c) we get equation (11) which is the commutating emf.

$$ \cos \theta = \sin (\theta + \pi/2) $$

(9)

$$ \rho \sin C = \sin A + m \sin B $$

(10a)

where

$$ \rho^2 = 1 + m^2 + 2 \cos (B-A) $$

(10b)

$$ C = \tan^{-1} \left( \frac{m \sin (B-A)}{1 + m \cos (B-A)} \right) $$

(10c)

$$ \cos (\theta - \pi/3 + \xi) - a \cos (\theta + \pi/3) $$

$$ = \sqrt{1 + a^2 - 2a \cos \alpha \sin (\theta + \pi/6 + \xi + \lambda)} $$

(11)

where $\alpha = \frac{2\pi - \xi}{3}$

(11a)

$$ \lambda = \tan^{-1} \left( \frac{-a \sin \alpha}{1 - a \cos \alpha} \right) $$

(11b)

Now we integrate equation (8) which gives us the relationship in equation (12).

$$ l_{dc} = \frac{V_m \sqrt{1 + a^2 - 2a \cos \alpha} - \cos (\theta + \pi/6 + \xi + \lambda)}{2\omega L_c} $$

(12)
\[1_{dc} = \frac{\sqrt{E_m^2 + a^2 - 2a \cos \sigma}}{2 \omega L_c} \left( \cos \left( a + \frac{\pi}{6} + \epsilon + \lambda \right) - \cos \left( \delta + \frac{\pi}{6} + \epsilon + \lambda \right) \right) \]  

(13)

But since we defined \( \delta \) as the angle at which equation (11) is equal to zero and \( \delta \) is normally greater than \( \pi/2 \) for inversion, we get equations (14 a-b).

\[
\delta + \frac{\pi}{6} + \epsilon + \lambda = \pi \quad \text{(14a)}
\]

\[
\cos \left( \delta + \frac{\pi}{6} + \epsilon + \lambda \right) = -1 \quad \text{(14b)}
\]

Substituting equation (14b) into equation (13) yields equation (15).

\[
\frac{2 \omega L_c}{E_m^2 + a^2 - 2a \cos \sigma} \quad \text{(15)}
\]

Now we can use equation (15) to determine \( a \) for any given firing angle.

**MODEL FOR SIMULATION**

Modeling Approach.

Three mathematical model algorithms were considered for the simulation: state equations, direct phase model, and symmetrical components. The state equation model is a straightforward method in which each dynamic element is evaluated by its time derivative. The disadvantage of this method is that it is rather bulky. The direct phase model makes a coordinate change from a fixed axis in "space" to one rotating with respect to an a.c. machine. This algorithm is useful mainly when studying rotating machines. Symmetrical components is a method
which is used to replace an unbalanced three phase system with an equivalent system of positive, negative and zero sequence components. But in order to use this method a symmetrical component model of the inverter bridge would have to be developed. The state variable model was selected because it is the simplest to set up. The model is composed of three parts: the d.c. model, inverter model, and a.c. model (see figure 3).

![Diagram of System Model](image)

**Figure 3** MODEL OF THE SYSTEM

The Inverter Model

The inverter can be simulated by a piecewise model with the assumption that the valves (SCR's) behave ideally. In referring back to Figure 1 we see that the mathematical equations which govern at any instant depend entirely on which valves are conducting or blocking.
Therefore, let us define \( S \) such that
\[
S = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23}
\end{bmatrix}
\]
(16)
where \( S_{1j} = \begin{cases} 
1 & \text{valve conducting} \\
0 & \text{valve blocked}
\end{cases} \)

Next we define \( x \) and \( y \) such that
\[
x = \sum_{1j} S_{1j} \quad \text{sum of upper valves conducting} \quad (17a)
\]
\[
y = \sum_{2j} S_{2j} \quad \text{sum of lower valves conducting} \quad (17b)
\]

Finally, we will define a function group as the set of differential equations for a particular valve configuration of \( S \). We then use the two quantities \( x \) and \( y \) to determine which function group is valid. (For the listing of each individual function group see appendix A.)

The A. C. Model

The a.c. model as shown in Figure 4 is composed of a set of harmonic filters and a transmission line. In order to simplify the model all components were assumed to behave ideally and a nominal L-R lumped model was assumed for the transmission line. One end of the model is connected to the inverter and the other is connected to an infinite bus-bar of constant voltage. Shown in Figure 4 is the assumed direction of the voltages and currents. Since the a.c. model is linearly continuous, there is only one set of equations which will govern. (For a listing of these equations see appendix B.)
THE D. C. MODEL

The d.c. model is similar to the a.c. model in that it contains a transmission line and a harmonic filter. In Figure 5 we see that the transmission line is again modeled as a lumped L-R circuit. One side of the model is connected to the d.c. source which is assumed to be either constant current or constant voltage, and is assumed to be perfectly smooth. The other end of the model is tied to the inverter.

\[ i_{HF} = \sum_{j=1}^{k-1} i_j + i_k + i_b \]

only one phase is shown.

Figure 4 THE A.C. MODEL
When we are operating the system with a constant current source, the d.c. transmission line equation has no valid meaning; but when operating as a constant voltage source then this equation must be included. This model can represent operation with the bridge conducting or blocked. (For a complete listing of all equations which govern in these four cases, please refer to appendix C.)

SIMULATION ALGORITHM

The model used for this study was partially based on the square Butte d.c. link and inverter station at Arrowhead, Minnesota. This inverter is a twelve pulse bridge which is actually two six pulse bridges with one electrically rotated 7/6 radius before the other bridge. In this case the bridges are in series on the d.c. side
and in parallel on the a.c. side. The transformers are connected as follows: bridge one low side (d.c.) wye; high side (a.c.) wye, bridge two low sides (d.c.) delta; high side wye. The wye-wye transformer has no voltage and current transformation problems since there is no phase shift. But this is not the case for the delta-wye transformer. For the delta-wye transformer the commutation voltage and a.c. current relationships are given in equations (19) and (20) and shown in Figure 6. 

\[
\text{emf}_{21} = \sqrt{3} v_2 \\
i_{r1} = \frac{i}{\sqrt{3}} (i_{r1} - i_{r3})
\]  

(19)  

(20)

Figure 6 DELTA - WYE TRANSFORMER RELATIONSHIPS

Therefore, the total current from the inverter is the sum of the
currents from the two bridges and the total d.c. voltage and commutation inductance is also the sum of the values for the two bridges.
(For a complete listing of all the values of the components of the model, see appendix C.)

The computer simulation of this entire system model was done by using an integration package known as Differential Systems Simulator Revision Two (DSS/2). This package was developed at Lehigh University and is basically a Runge Kutta integrating routine with an error estimating and correcting feature. At each interval of time the matrix $S$ is evaluated and those equations which are valid are used. The next valve to fire is "turned on" at each advance of $\pi/6$ electrical radians; this means we are holding the firing angle, $\alpha$, constant. When the current in a valve reaches zero the valve is "turned off". After this has been repeated for 5 cycles the results are plotted and a harmonic analysis is performed on certain selected variables. This is based on the assumption that the voltage will reach a steady state within 5 cycles following a disturbance. The initial conditions were determined by assuming ideal behavior of the inverter. That is, we operated the inverter model by itself with $I_{dc}$ being smooth and $V_{ac}$ being a pure sinusoidal of frequency 60 Hz. Then we made a harmonic analysis of the a.c. current and d.c. voltage. Using these results and complex arithmetic, the a.c. and d.c. responses were determined in terms of their fundamental and characteristic harmonics, up to the 49th harmonic. Then the sum of the real parts was used as our initial conditions.

Two types of studies were made, constant current source and
constant voltage source. For each study six simulations were done, one with no fault and five with different values of fault induc-
tions, $L_f$. In each run with a fault the fault was started at time $= 0$ sec. All simulation runs were started at time $= -0.000417$ sec., (9 electrical degrees before the fault was initiated) with a basic
time interval of $= 0.00139$ sec. An extra simulation was done in
which the fault was removed at the first zero current crossing after
5 cycles, with a total simulated time of 10 cycles.

RESULTS

Tables 1 and 2 are the tabulation for the fault simulation. The
first table is for the case of constant current source and the second
one is the case of constant voltage. $I_{fl}$ is the a.c. line current
minus the load current. Also, "a" is the ratio of the line voltage
of the fault to the line voltage of the load.

TABLE 1

<table>
<thead>
<tr>
<th>$L_f$ (mH)</th>
<th>$V_1$ (kv)</th>
<th>a (p.u.)</th>
<th>$I_{fl}$ (ka)</th>
<th>Commutation Failure?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>15.3</td>
<td>0.081</td>
<td>80.9</td>
<td>Yes</td>
</tr>
<tr>
<td>1.0</td>
<td>28.4</td>
<td>0.150</td>
<td>74.8</td>
<td>Yes</td>
</tr>
<tr>
<td>10.</td>
<td>121</td>
<td>0.639</td>
<td>32.9</td>
<td>Yes</td>
</tr>
<tr>
<td>100.</td>
<td>179.</td>
<td>0.946</td>
<td>4.94</td>
<td>No</td>
</tr>
<tr>
<td>500.</td>
<td>187.</td>
<td>0.989</td>
<td>1.11</td>
<td>No</td>
</tr>
<tr>
<td>$\infty$</td>
<td>189.</td>
<td>1.0</td>
<td>0.0</td>
<td>No</td>
</tr>
</tbody>
</table>
Let us look at the value of "a" as a function of the fault inductance of $L_f$. Firstly, we see that "a" tends to go to zero when $L_f$ is zero and becomes one when $L_f$ goes to infinity. Equation (21) gives a function which meets these characteristics.

$$a = \frac{L_f}{X_c + L_f} \quad (21)$$

where $X_c = 0.00565$

We can see from Figures 7 and 8 that this relationship does appear to exist. But what is $X_c$ dependent upon? From Table 2 we deduce that the d.c. side of the inverter does not control $X$. Therefore, we can claim that $X_c$ is dependent largely on the a.c. system and the harmonic filters. The breakpoint $X_c$ was determined by averaging the $X_c$'s from each run.

### Table 2

**CONSTANT VOLTAGE SOURCE**

| $L_f$ (mh) | $|V_1|$ (kv) | $a$ (p.u.) | $|I_f|$ (ka) | Commutation Failure? |
|------------|-------------|------------|-------------|---------------------|
| 0.5        | 15.3        | 0.081      | 81.1        | Yes                 |
| 1.0        | 28.4        | 0.150      | 74.8        | Yes                 |
| 10.0       | 121.        | 0.639      | 31.5        | Yes                 |
| 100.       | 179.        | 0.946      | 4.78        | No                  |
| 500        | 187.        | 0.989      | 1.01        | No                  |
| ∞          | ∞           | 1.0        | 0.0         | No                  |

| $L_f$ (mh) | $|V_1|$ (kv) | $a$ (p.u.) | $|I_f|$ (ka) | Commutation Failure? |
|------------|-------------|------------|-------------|---------------------|
| 0.5        | 15.3        | 0.081      | 81.1        | Yes                 |
| 1.0        | 28.4        | 0.150      | 74.8        | Yes                 |
| 10.0       | 121.        | 0.639      | 31.5        | Yes                 |
| 100.       | 179.        | 0.946      | 4.78        | No                  |
| 500        | 187.        | 0.989      | 1.01        | No                  |
| ∞          | ∞           | 1.0        | 0.0         | No                  |
Now let us look at the relationship between $I_{f1}$ and $L_f$. As $L_f$ goes to infinity $I_{f1}$ approaches zero. Also, when $L_f$ is zero $I_{f1}$ reaches a maximum value. Equation (22) is a relationship which has these characteristics.

$$I_{f1} = \frac{b}{L_f + X_b}$$  \hspace{1cm} (22)

Table 3 is the tabulation of $b$ and $X_b$ for the two cases and Figures 9 and 10 are the plots of the best fit curve.

<table>
<thead>
<tr>
<th>Case</th>
<th>$b$ (amp-Henries)</th>
<th>$X_b$ (Henries)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Current</td>
<td>504</td>
<td>0.00572</td>
</tr>
<tr>
<td>Constant Voltage</td>
<td>525</td>
<td>0.006</td>
</tr>
</tbody>
</table>

The last three simulations of the constant voltage case required the following changes from the other simulations, in order to prevent collapse of the computer program. The problem was a large current transient in the inverter, which caused the model to break down. To get around this problem a "control" option was introduced, so that if the d.c. line current became larger than a set value, then the source voltage was reduced proportionately to the current. Also, the d.c. line current was not allowed to exceed an arbitrarily chosen maximum, and the smoothing choke was increased from 60 mH to 120 mH. When these modifications were incorporated, the model continued to operate.
Equation (16) presents a relationship between $\alpha$, the firing angle, and $a$, the minimum per unit value of the voltage for normal operations. This model was operated with a constant firing angle of 2.443 rad. Using this angle in equation (16) we obtained a value of $a = 0.057$. Using this value in equation (21) we obtained $L_f$ equal to 0.034 mH. Two additional simulations were made with $L_f$ equal to 0.034 and 0.033. In the first case there was no commutation failure; but in the second case commutation failure did occur.

To determine whether $X_c$ is dependent on the a.c. system, we increased the impedance of the a.c. transmission line $z_t$ by a factor of ten. The results are tabulated in Table 4.

### Table 4: Effect of Increased A.C. Line Impedance

<table>
<thead>
<tr>
<th>$L_f$ (mH)</th>
<th>$V_1$ (kv)</th>
<th>$a$ (p.u.) for $z_t \times k$</th>
<th>$a$ (p.u.) for $z_t \times 10$</th>
<th>$X_c$ (mH) for $z_t \times 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>118</td>
<td>0.946</td>
<td>0.624</td>
<td>60.0</td>
</tr>
<tr>
<td>10</td>
<td>28.4</td>
<td>0.639</td>
<td>0.150</td>
<td>57.0</td>
</tr>
</tbody>
</table>

Finally, in order to determine whether the bridge would recover from the voltage drop due to the fault, a run was made in which the fault was turned on at time $t = 0$ and, after five cycles, the fault was removed at the first current zero. Figures 11 through 15 show the results for $L_f = 0.033$ and constant d.c. current source. We can see from Figure 11 that the bridge did not recover. Several other runs were also made where $L_f$ was varied, the firing angle was changed when the fault was removed, and the a.c. transmission line...
impedance was reduced. The bridge did not recover from any of these cases. One successful recovery procedure has been to bypass the bridge, start it up as a rectifier, and then advance the firing angle and block the bypass circuit. This procedure is the same as used when first starting up the bridge, with both the a.c. and d.c. lines energized.

**OBSERVATIONS AND CONJECTURES**

**BASED ON SIMULATION RUNS**

Listed below are some observations of the simulations and conjectures about the results made by the author.

1. The breakpoint in the fault current and voltage vs. $L_f$, the fault inductance, is seen to be very close in value to the a.c. transmission line impedance divided by the fundamental frequency.

2. The maximum a.c. current fed to the fault is close in value to the infinite bus-bar voltage divided by the transmission line impedance.

3. The relationships obtained for the line voltage and a.c. current fed to the fault vs. the fault inductance behave the same as the voltage and current divider laws.

4. The inability of the bridge to recover was due to a very large ripple in the d.c. current from the bridge. What appeared to happen is that during commutation the d.c. current was higher than normal. This would make the time required for commutation larger to the extent that the commutating emf would change.
polarity before commutation is completed.

5. It was observed that the a.c. line current has a negative d.c. transient component. This means that the a.c. infinite bus-bar is supplying the d.c. current transient. The author believes that this is due to the initial conditions, that is the actual value of the state variables at the time the fault was initiated.

CONCLUSIONS

On the basis of this work, we can describe inverter operation when subjected to an a.c. system fault as follows:

1. The expression for the a.c. line voltage to ensure normal operation in terms of the firing angle $a$, is given in equation (15).

2. The line voltage is related to $L_f$, the fault inductance by the equation, $a = \frac{L_f}{L_f + x_c}$. Where $x_c$ depends on the circuit configuration on the a.c. side of the inverter.

3. The a.c. line current fed to the fault is related to $L_f$ by the equation $I_{f1} = \frac{b}{L_f + x_c}$. Where $x_c$ and $b$ depend on the circuit configuration on the a.c. side of the inverter.

4. The inverter did not return to normal operation when the fault was removed. The reduction of the ripple on the d.c. current from the bridge will aid in the recovery of the bridge. This is from the fact that Commutation failure is a self-correcting con-
dition; that is, when the abnormal voltage and current conditions are removed from the bridge the bridge will return to normal operation after one electrical cycle.
Figure 8 A.C. Voltage vs. Fault Inductance Constant Voltage

Fitted Curve by Calculation

+ Computed Points From Simulation Run

Lf in Henries

a in per unit

0.0001 0.001 0.01 0.1 1.0

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

a in per unit

24
Figure 9 A.C. Current to Fault vs. Fault Inductance Constant Current
Figure 10 A.C. Current to Fault vs. Fault Inductance Constant Voltage

$\Phi_1$ in kiloamps

$L_f$ in Henries

$\Phi_1$ in kiloamps
Figure 11 A.C. Current to the Inverter

Amps X 100
Figure 15 D.C. Line Voltage

Volts X 10,000

Cycles
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Uhlmann, E., Power Transmission by Direct Current. Berlin: Springer Verlag., 1975

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Listed below are the function groups for the bridge operation. Each group is defined by two numbers where the first is the number of valves which are conducting in the lower row, and the second is the number in the upper row (see Figure 16). Where $r_{ij}$ is the current in the valve $ij$.

![Figure 16 The Inverter Model](image)
<table>
<thead>
<tr>
<th>Function Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,0)</td>
<td>No phase indices</td>
</tr>
<tr>
<td></td>
<td>$i_d = 1 - r_k = 0$ for $j = 1, 2, 3$ and $k = 1, 2$</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} = 0$</td>
</tr>
<tr>
<td>(0,1)</td>
<td>Phase number of the conducting valve of the upper row.</td>
</tr>
<tr>
<td></td>
<td>Same as group (0.0)</td>
</tr>
<tr>
<td>(1,0)</td>
<td>Phase number of the conducting valve of the lower row.</td>
</tr>
<tr>
<td></td>
<td>Same as group (0.0)</td>
</tr>
<tr>
<td>(0,2)</td>
<td>Phase numbers of conducting valves of the upper row.</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} = \frac{1}{2L_c} (V_1 - V_n)$</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} = -\frac{d}{dt} i_l$</td>
</tr>
<tr>
<td></td>
<td>$i_l = r_{1l} = r_{ln} = i_n$</td>
</tr>
<tr>
<td>(2,0)</td>
<td>Phase numbers of the conducting valves in the lower row.</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} = \frac{1}{2L_c} (V_m - V_n)$</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} = \frac{d}{dt} i_m$</td>
</tr>
<tr>
<td></td>
<td>$i_m = r_{2m} = -i = r_{2n}$</td>
</tr>
</tbody>
</table>
\text{(0,3)} \quad 1 = 1 \quad m = 2 \quad n = 2

\frac{d}{dt} i_j = \frac{1}{L_c} (V_j - \frac{1}{\frac{L}{3}} \sum_{k=1}^{3} V_k) \quad j = 1, 2, 3

r_{ij} = i_j

\text{(3,0)} \quad 1 = 1 \quad m = 2 \quad n = 3

Same as group (0,3)

\text{(1,1)}

1 - phase number of the upper row.

m - phase number of the lower row.

i_l = i \quad n = r \quad l_1 = \frac{r_m}{2m} \quad dc

\frac{d}{dt} i_l = - \frac{d}{dt} i_m = \frac{d}{dt} i \quad dc

\text{(1,2)}

For non-shorted state

l, n - phase numbers of upper row. (1

m - phase number of the lower row.

\frac{d}{dt} i_l = \frac{1}{2L_c} (V_l - V_n) + \frac{1}{2} \frac{d}{dt} i \quad dc

\frac{d}{dt} i_n = \frac{1}{2L_c} (V_n - V_l) + \frac{1}{2} \frac{d}{dt} i \quad dc

\frac{d}{dt} i_m = - \frac{d}{dt} i \quad dc

i_l + i \cdot i_n = - i_m = i \quad dc = r_{2m}

i_l = r_{1l} \quad i_n = r_{1n}

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For shorted state

1, n - phase numbers of the upper row

m - phase number of the lower row. (1 < n)

\[
\frac{d}{dt} i_1 = \frac{1}{2L_c} (V_1 - V_n)
\]

\[
\frac{d}{dt} i_n = - \frac{d}{dt} i_1
\]

\[
\frac{d}{dt} i_m = 0
\]

\[
\begin{align*}
R_{11} &= \frac{1}{L_c} \frac{d}{dt} i_1 \\
R_{1n} &= \frac{1}{L_c} \frac{d}{dt} i_n \\
R_{2m} &= \frac{1}{L_c} \frac{d}{dt} i_{2m}
\end{align*}
\]

(2, 1)

For non-shorted state

1 - phase number of the upper row.

m, n - phase numbers of the lower row. (m < n)

\[
\frac{d}{dt} i_m = \frac{1}{2L_c} (V_m - V_n) + \frac{1}{L_c} \frac{d}{dt} i_{dc}
\]

\[
\frac{d}{dt} i_n = \frac{1}{2L_c} (V_n - V_m) + \frac{1}{L_c} \frac{d}{dt} i_{dc}
\]

\[
\frac{d}{dt} i_1 = \frac{d}{dt} i_{dc}
\]

\[
i_l = i_n - i_n = i_{dc}
\]

\[
r_{2m} = i_m \quad r_{2m} = -i_n \quad r_{11} = i_{dc}
\]
For shorted state

\( l \) - phase number of the upper row.

\( m, n \) - phase numbers of the lower row. \((1=m)\)

\[
\frac{d}{dt} i_m = \frac{1}{2L_c} \left( V_m - V_n \right)
\]

\[
\frac{d}{dt} i_n = -\frac{d}{dt} i_m
\]

\[
\frac{d}{dt} i_1 = 0
\]

\[
\begin{align*}
    r_{1l} &= i_{dc} \quad r_{2m} = i_{dc} - i_m \quad r_{2n} = -i_n \\
    (1,3)
\end{align*}
\]

\( l \) - phase number of the lower row.

\( m, n \) - phase numbers of the others such that \( m<n \).

\[
\frac{d}{dt} i_j = \frac{1}{L_c} \left( V_j - \frac{1}{3} \sum_{k=1}^{3} V_k \right) \quad j = 1, 2, 3
\]

\[
\begin{align*}
    r_{1l} &= i_{1l} + i_{dc} \quad r_{1m} = i_m \quad r_{1n} = i_n \\
    r_{21} &= i_{dc} \\
    (3,1)
\end{align*}
\]

\( l \) - phase number of the upper row.

\( m, n \) - phase numbers of the others such that \( m<n \).

\[
\frac{d}{dt} i_j = \frac{1}{L_c} \left( V_j - \frac{1}{3} \sum_{k=1}^{3} V_k \right) \quad j = 1, 2, 3
\]

\[
\begin{align*}
    r_{1l} &= i_{dc} \quad r_{21} = i_{dc} \quad r_{2m} = -i_m \\
    r_{2n} &= -i_n
\end{align*}
\]

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(2,2)

1 - phase number of the valves in the upper and lower rows.

m - phase number of the other valve in the upper row.

n - phase number of the other valve in the lower row.

\[
\frac{d}{dt} i_j = \frac{3}{L_c} \left( V_j - \frac{1}{3} \sum_{k=1}^{3} V_k \right), \quad j = 1, 2, 3
\]

\[
r_{11} = i_{dc}, \quad r_{1n} = i_n, \quad r_{21} = i_{dc}
\]

\[
r_{2n} = i_m
\]

(2,3) Undefined State - Any time where more than four valves are conducting the model is arbitrarily shut down.

(3,2) Undefined State

(3,3) Undefined State
APPENDIX B

A. C. MODEL EQUATIONS

The state equations for the a. c. system and the harmonic filters are listed below (refer to Figure 5).

\[ b_k = \sum_{j=1}^{k-1} b_j - i_k - i_r - i_f \]  \hspace{1cm} (B1)

\[ \frac{d}{dt} V_F + \frac{b}{C} \]  \hspace{1cm} (B2)

\[ \frac{d}{dt} V_k = \frac{d}{dt} V_F - \frac{i_k}{C_k} \]  \hspace{1cm} (B3)

\[ \frac{d}{dt} V_j = \frac{d}{dt} V_F - \frac{i_j}{C_j} \]  \hspace{1cm} (B4)

\[ \frac{d}{dt} i_j = \frac{1}{L_j} (V_j - R_j i_j) \]  \hspace{1cm} (B5)

\[ \frac{d}{dt} i_f = \frac{1}{L_f} (V_F - R_f i_f) \]  \hspace{1cm} (B6)

\[ \frac{d}{dt} i_s = \frac{1}{L_s} (V_F - V_s - R_s i_s) \]  \hspace{1cm} (B7)

\[ \frac{d}{dt} i_k = \frac{1}{R_k} \frac{d}{dt} V_k + \frac{V_k}{L_k} \]  \hspace{1cm} (B8)
APPENDIX C

D. C. MODEL EQUATIONS

The state equations of the d. c. model are listed for the four possible operating conditions. Refer to Figure 4 for the circuit diagram.

1. Bridge conducting; Constant voltage source:

\[ V_{FP} = \left( \frac{d}{dt} i_d - \frac{d}{dt} i_c - \frac{d}{dt} i_1 \right) L_2 + \left( i_{dc} - i_1 - i_1 \right) R_2 \]  
\hspace{1cm} (C1)

\[ \frac{d}{dt} V_D = \frac{i_{dc} - i_1}{C_1} \]  
\hspace{1cm} (C2)

\[ \frac{d}{dt} V_{DP} = \frac{i_{dc} - i_1 - i_1}{C_2} \]  
\hspace{1cm} (C3)

\[ \frac{d}{dt} i_1 = \frac{(E - V_D - V_{FD} - R_1 i_1)}{L_1} \]  
\hspace{1cm} (C4)

\[ \frac{d}{dt} i_{dc} = \frac{(V_D + V_{DP} + V_{FP} - \Xi A)}{(L_s + \Xi B)} \]  
\hspace{1cm} (C5)

\[ \frac{d}{dt} i_1 = \frac{(V_{FP} - R_1 i_1)}{L_1} \]  
\hspace{1cm} (C6)

Bridge conducting; Constant current source:

In this case only equations (C1) and (C4) change as follows:
\[ V_{FP} = \left( \frac{d}{dt} i_{dc} - \frac{d}{dt} i_1 \right) L_2 + (i_{dc} - i_1 - i_\xi) R_2 \]  (C7)

\[ \frac{d}{dt} i_i = 0 \]  (C8)

3. Bridge not conducting; Constant voltage source:
In this case, only equations (C1) and (C5) change from the first case and \( i_{dc} \) is equal zero.

\[ V_{FP} = \left( \frac{d}{dt} i_1 + \frac{d}{dt} i_\xi \right) L_2 - (i_1 + i_\xi) R_2 \]  (C9)

\[ \frac{d}{dt} i_{dc} = 0 \]  (C10)

4. Bridge not conducting; Constant current source: This case is like case No. 3 except with \( \frac{d}{dt} i \) equaling zero. Therefore equations (C1) and (C4) are changed and equation (C10) is included in this case.

\[ V_{FP} = -\left( \frac{d}{dt} i_1 \right) L_2 - (i_1 + i_\xi) R_2 \]  (C11)

\[ \frac{d}{dt} i_\xi = 0 \]  (C12)

\[ \frac{d}{dt} i_{dc} = 0 \]  (C13)
APPENDIX D
MODEL PARAMETERS

Listed below is the value of all the components used in all
simulation except where noted.

Inverter

\[ L_c = 0.03785 \text{ H} \]

D.C.

\[
\begin{align*}
L_1 &= 0.0338 \text{ H} \\
L_2 &= 0.0122 \text{ H} \\
L_s &= 0.06 \text{ H} \\
L_f &= 0.87 \text{ H}
\end{align*}
\]

\[
\begin{align*}
R_2 &= 1.32 \Omega \\
R_2 &= 0.0 \Omega \\
R_i &= 15.08 \Omega
\end{align*}
\]

C. 1 = 6 \mu F

A. C.

\[
\begin{align*}
L_{11} &= 0.05 \text{ H} \\
L_{13} &= 0.0535 \text{ H} \\
L_k &= 0.009 \text{ H} \\
L_s &= 0.00562 \text{ H}
\end{align*}
\]

\[
\begin{align*}
R_{11} &= 0.0 \Omega \\
R_{13} &= 0.0 \Omega \\
R_k &= 166.0 \Omega \\
R_s &= 0.069 \Omega
\end{align*}
\]

\[
\begin{align*}
C_{11} &= 1.16 \mu F \\
C_{13} &= 0.77 \mu F \\
C_k &= 1.5 \mu F \\
C_b &= 3.0 \mu F
\end{align*}
\]
John H. Hobson, the son of John F. and Marie L. Hobson, was born on February 19, 1952 in Abington, Pennsylvania, U.S.A. He attended Abington High School from 1967 to 1970. In May, 1975 he graduated cum laude from Widener College with the degree of Bachelor of Science in Engineering. In the fall of 1975, he started attending Lehigh University for his graduate work, and is presently attending both Lehigh University and the University of Pennsylvania. Mr. Hobson is a member of Tau Beta Pi and Alpha Chi honor societies. He has gained experience as a part time technician at the Franklin Institute Research Laboratories since January, 1974.