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Analysis Of Symmetrical Short-Circuit Current And Performance Of Synchronous Generators

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Abstract

This paper focuses on the transient behaviour and performance of a synchronous machine because these conditions may have dominant effect on the application of synchronous machine and may demand special attention in its design. The general problem therefore, requires knowledge of the solution of the sub-transient, transient and synchronous reactances and their associated time constants. The above stated parameters are estimated by analysing the current waveforms of a fault applied at the generator terminals as presented in this paper.

Keywords: Transient, Sub-transient, synchronous machines, short-circuit

"1. Introduction"

The events within a generator subjected to a sudden short-circuit depend on several factors, including (i) the instant in the cycle at which short-circuit is initiated (ii) the load and excitation of the machine at this time (iii) the extent of the fault (i.e. the number of phase windings involved and the distance of the fault from the machine terminals) and (iv) the constructional features of the machine that affect flux leakage and damping.

"1.1 Short-Circuit Time Interval"

The time immediately following a short circuit may be divided into three successive intervals:

1. A very short time (e.g. one or two periods of the supply frequency) during which the conditions are largely dependent upon the flux linking the stator and rotor windings at the instant of fault initiation.
2. A subsequent interval of transient decay of current amplitudes consequent upon damping and the rise of armature reaction.
3. A final period which is steady state short circuit conditions. A machine will normally be open-circuited before this period is reached.

"1.2 Short-Circuit Current Envelope"

On a three-phase dead short-circuit, the a.c components of the phase currents (i.e. the currents that remain after the d.c transient components have been extracted) occupy identical envelope shapes, of which fig. 1 below is typical.

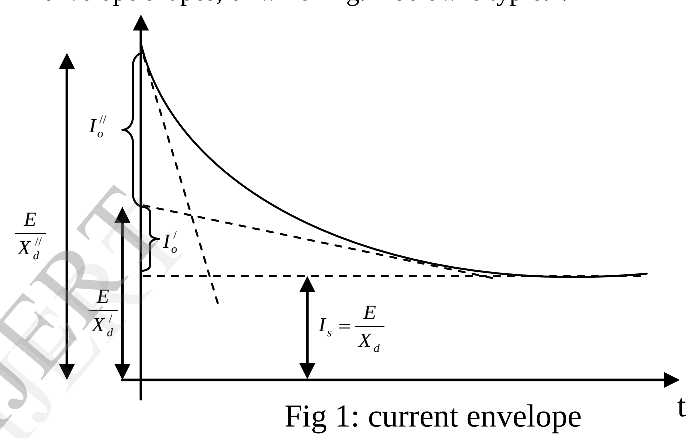

Fig 1: current envelope

At the beginning, however, there is a much rapid rate of decay with a time constant of 0.2s or less. Extrapolation of the main part of the envelope back to zero time would give a peak current of $E_o / X_d^{/}$: the actual current peak at zero time, given by $E_o / X_d^{//}$, is in fact considerably greater.

"2. Simplified Machine Model"

For a terminal short-circuit, all the effective reactances (sub-transient, transient and steady-state or synchronous reactances) are d-axis quantities. If the short-circuit occurs at a point remote from the generator terminals into the connected network, the phase angle may be less and quadrature reaction effects may appear together with some increase in the resistance and inductance parameters concerned in the short-circuit paths.

For a steady-state operation, generators are represented with a constant e.m.f behind a synchronous reactance, X_s under transient conditions. The machine reactance changes due to the effect of the armature (transformer) reaction and eddy currents in the damping circuits.

For analysis, it is useful to imagine the synchronous reactance as three components;
(i) Direct axis sub-transient reactance (ii) Direct axis transient reactance (iii) Direct axis steady-state reactance
Each of these reactances has its associated time constant.

"3. Model Visualisation"

A generator has three windings separated by 120^0; each phase will have a different d.c component depending on the point of the voltage cycle at which the short-circuit occurs

$$I_{dc-a} = \frac{E_o x\sqrt{2}}{X_d^{//}}(\sin\delta)e^{-\frac{t}{\tau_a}}$$

The current of phase-a is given by combining the a.c and d.c components using superposition. This is given by the expression

$$I_{dc} = E_o x\sqrt{2}\left[\left(\frac{1}{X_d^{//}} - \frac{1}{X_d^{/}}\right)\right]e^{-\frac{t}{\tau_d^{//}}}[\sin(\omega t+\delta)] +$$

$$E_o x\sqrt{2}\left[\left(\frac{1}{X_d^{/}} - \frac{1}{X_d}\right)\right]e^{-\frac{t}{\tau_d^{/}}}[\sin(\omega t+\delta)] +$$

$$E_o x\sqrt{2}\left[\frac{1}{X_d}\right][\sin(\omega t+\delta)]$$

The expression for the stator current for the simplified machine model does not include the effect of the decaying exponential unidirectional current.
The d.c component is a function of the machine's rotor position, which is indicated by δ when the short circuit is applied at t = 0.

The time constant associated with the decay of the d.c component is known as the armature short circuit time constant, τ_d. Typical time constants range from 0.05 to 0.17s.

"4. Data Preparation"

For the purpose of this analysis, no-load or open-circuit terminal voltage, E_o = 4.6kV. The current waveform is divided into three periods. These are sub-transient, transient and steady-state periods.
First determine the synchronous reactance, X_d using the current value, I_d where the waveform envelope becomes constant, i.e.

$$I_d = \frac{I_{d(rms)}}{\sqrt{2}};\ X_d = \frac{E_o}{I_d}$$

Second, using the part of the envelope between the sub-transient time period and the steady-state time period.

- The steady-state current is subtracted from the transient current.
- The logarithmic curve of the envelope is plotted with respect to linear time as a straight line.
- The y-intercept and the slope are obtained from the graph, i.e.

$$\Delta i^{/} = (I_d^{/} - I_d)e^{-\frac{t}{\tau_d^{/}}}$$

Take natural logarithm of both sides

$$In\Delta i^{/} = In(I_d^{/} - I_d) - \frac{t}{\tau_d^{/}}$$
$$= c^{/} - m^{/}t$$

Where

$$c^{/} = In(I_d^{/} - I_d)$$

or $$I_d^{/} = e^{c^{/}} + I_d$$

$$X_d^{/} = \frac{E_o}{I_d^{/}}$$

and $$m^{/} = \frac{1}{\tau_d^{/}}$$

or $$\tau_d^{/} = 1/m^{/}$$

where
$c^{/}$ = intercept on the vertical axis
$m^{/}$ = slope of the graph
Third, using the two cycles of the fault current envelope, the steady-state and transient currents are subtracted from the sub-transient current.

- The logarithmic curve of the envelope is plotted with respect to linear time as a straight line
- The y-intercept and the slope are obtained from the graph, i.e.

$$\Delta i^{//} = (I_d^{//} - I_d^{/})e^{-\frac{t}{\tau_d^{//}}}$$

Take natural logarithm of both sides

$$In\Delta i^{//} = In(I_d^{//} - I_d^{/}) - \frac{t}{\tau_d^{//}}$$
$$= c^{//} - m^{//}t$$

Where

$$c^{//} = In(I_d^{//} - I_d^{/})$$

or $$I_d^{//} = e^{c^{//}} + I_d^{/}$$

$$X_d^{//} = \frac{E_o}{I_d^{//}}$$

and $$m^{//} = \frac{1}{\tau_d^{//}}$$

or $\tau_d^{//} = 1/m^{//}$

where
$c^{//}$ = intercept on the vertical axis
$m^{//}$ = slope of the graph

"5. Result"

The table 1 shows the data obtained from the oscillogram for the phase-a of a generator terminal under a three-phase fault.

The current envelope has an asymmetry. The d.c component is extracted and plotted separated against time and the time constants obtained from the duration between the initial value and 0.368 of this value. The remaining symmetrical envelope is plotted as in the upper part of fig1 and rest of the constants obtained. For this purpose, the following columns are added to the table: $I_{ac} = \frac{1}{2}(I_p + I_n)$ x oscillograph scale factor gives the a.c component in amps, and $I_{dc} = \frac{1}{2}(I_p - I_n)$ x oscillograph scale factor yields the amplitude (above and below current zero) of the d.c component in amps. The results are:

The following relation can be used to find the rated current

$$I_{rated} = \frac{S(VA)}{E_o x\sqrt{3}}$$

Where
S = machine rating
E_o= no-load voltage

For the purpose of this work, S = 56MVA and E_o= 4.6kV. That is, the r.m.s value of the rated current is

$$I_{rated} = \frac{56x10^3}{4.6x\sqrt{3}} = 7.03\text{kA}.$$

But the peak value of the rated current is $I_{peak} = I_{rms} x\sqrt{2}$ = 7.03 x 1.414 = 9.94kA or 1.0pu.

As shown on the attached graph sheet and the table of values in the appendix of this work.

The initial peak a.c component is 362.8A

But $X_d^{//} = \frac{E_o}{I_d^{//}}$

Hence, $X_d^{//} = \frac{4.6x10^3}{362.8}$ = 12.68Ω

Extrapolating the plot gives the transient component peak as $I_d^{/} = 268A$.

But $X_d^{/} = \frac{E_o}{I_d^{/}}$

Hence, $X_d^{/} = \frac{4.6x10^3}{268}$ = 17.16Ω

Similarly, the steady-state short-circuit current is 130.5A peak.

But $X_d = \frac{E_o}{I_d}$

Hence, $X_d = \frac{4.6x10^3}{130.5}$ =32.25Ω

The difference 362.8 – 268.0 = 94.8A between the sub-transient and transient currents is shown to fall to 94.8 x 0.368 = 34.88A in $\tau_d^{//} = 0.018\sec$. Similarly, the difference 268.0 – 130.5 = 137.5A between the transient and steady-state currents fall to 137.5 x 0.368 = 50.6A in $\tau_d^{/} = 0.14\sec$.

A separate plot of the d.c component against time is also attached. By treating it in like manner, the intercept on the vertical axis on the graph of the d.c component against time is 142A.

Hence, 0.368 x 142 = 52.25A which gives $\tau_d = 0.097\sec$.

The parameters required are therefore

$$I_d^{//} = 362.8A$$
$$I_d^{/} = 268.0A \text{ and}$$
$$I_d = 130.5A$$
$$X_d^{//} = 12.68\Omega$$
$$X_d^{/} = 17.16\Omega \text{ and}$$
$$X_d = 35.25\Omega$$
$$\tau_d^{//} = 0.018\sec.$$
$$\tau_d^{/} = 0.14\sec.$$
$$\tau_d = 0.097\sec.$$

"6. Conclusion"

This paper has analysed a 3-phase current envelope and has shown the required parameters (the reactances and the associated time constants) for a three-phase short-circuit on the terminals of the synchronous generator.

"7. References"

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Appendix

"Table 1: Input Data"

S/N	t (sec)	$I_{\max}(cm)$	$I_{\min}(cm)$	$\lvert I_{\max}\rvert = 261xI_{\max}$ (A)	$\lvert I_{\min}\rvert = 261xI_{\min}$ (A)	$\lvert I_{ac}\rvert = \frac{1}{2}(\lvert I_{\max}\rvert + \lvert I_{\min}\rvert)$ (A)	$\lvert I_{dc}\rvert = \frac{1}{2}(\lvert I_{\max}\rvert - \lvert I_{\min}\rvert)$ (A)
1	0.00	0.40	2.30	104.4	600.3	352.4	248.0
2	0.01	0.40	2.10	104.4	548.1	326.3	221.9
3	0.02	0.45	1.87	117.5	488.1	302.8	185.3
4	0.03	0.40	1.60	104.4	417.6	261.0	156.6
5	0.04	0.41	1.50	107.0	391.5	249.3	142.2
6	0.05	0.42	1.40	109.6	365.4	237.5	127.9
7	0.06	0.44	1.20	114.8	313.2	214.0	99.2
8	0.07	0.60	1.10	156.6	287.1	221.9	65.3
9	0.08	0.48	1.10	125.3	287.1	206.2	80.9
10	0.09	0.50	1.12	130.5	292.3	211.4	80.9
11	0.10	0.60	1.00	156.6	261.0	208.8	52.2
12	0.11	0.60	0.95	156.6	248.0	202.3	45.7
13	0.12	0.60	0.90	156.6	234.9	195.8	39.2
14	0.13	0.61	0.89	159.2	232.3	195.8	36.5
15	0.14	0.60	0.90	156.6	234.9	195.8	39.2
16	0.15	0.61	0.80	159.2	208.8	184.0	24.8
17	0.16	0.60	0.79	156.6	206.2	181.4	24.8
18	0.17	0.63	0.75	164.4	195.8	180.1	15.7
19	0.18	0.61	0.73	159.2	190.5	174.9	15.7
20	0.19	0.64	0.70	167.0	182.7	174.9	7.8
21	0.20	0.64	0.71	167.0	185.3	176.2	9.1
22	0.21	0.63	0.70	164.4	182.7	173.6	9.1
23	0.22	0.62	0.70	161.8	182.7	172.3	10.4
24	0.23	0.64	0.70	167.0	182.7	174.9	7.8
25	0.24	0.65	0.68	169.7	177.5	173.6	3.9
26	0.25	0.68	0.69	177.5	180.1	178.8	1.3
27	0.26	0.70	0.69	182.7	180.1	181.4	1.3
28	0.27	0.70	0.70	182.7	182.7	182.7	0.0
29	0.28	0.71	0.70	185.3	182.7	184.0	1.3
30	0.29	0.69	0.70	180.1	182.7	181.4	1.3
31	0.30	0.69	0.68	180.1	177.5	178.8	1.3
32	0.31	0.68	0.68	177.5	177.5	177.5	0.0
33	0.32	0.70	0.62	182.7	161.8	172.3	10.4
34	0.33	0.68	0.62	177.5	161.8	169.7	7.8
35	0.34	0.65	0.62	169.7	161.8	165.7	3.9

36	0.35	0.65	0.61	169.7	159.2	164.4	5.2
37	0.36	0.65	0.60	169.7	156.6	163.1	6.5
38	0.37	0.63	0.60	164.4	156.6	160.5	3.9
39	0.38	0.61	0.61	159.2	159.2	159.2	0.0
40	0.39	0.60	0.61	156.6	159.2	157.9	1.3
41	0.40	0.60	0.60	156.6	156.6	156.6	0.0
42	0.41	0.60	0.61	156.6	159.2	157.9	1.3
43	0.42	0.60	0.60	156.6	156.6	156.6	0.0
44	0.43	0.60	0.60	156.6	156.6	156.6	0.0
45	0.44	0.59	0.60	154.0	156.6	155.3	1.3
46	0.45	0.60	0.60	156.6	156.6	156.6	0.0
47	0.46	0.60	0.60	156.6	156.6	156.6	0.0
48	0.47	0.60	0.60	156.6	156.6	156.6	0.0
49	0.48	0.60	0.51	156.6	133.1	144.9	11.7
50	0.49	0.60	0.60	156.6	156.6	156.6	0.0
51	0.50	0.60	0.60	156.6	156.6	156.6	0.0
52	0.51	0.60	0.59	156.6	154.0	155.3	1.3
53	0.52	0.55	0.56	143.6	146.2	144.9	1.3
54	0.53	0.55	0.55	143.6	143.6	143.6	0.0
55	0.54	0.55	0.55	143.6	143.6	143.6	0.0
56	0.55	0.60	0.55	156.6	143.6	150.1	6.5
57	0.56	0.60	0.55	156.6	143.6	150.1	6.5
58	0.57	0.60	0.54	156.6	140.9	148.8	7.8
59	0.58	0.60	0.53	156.6	138.3	147.5	9.1
60	0.59	0.59	0.52	154.0	135.7	144.9	9.1
61	0.60	0.59	0.51	154.0	133.1	143.6	10.4
62	0.61	0.59	0.54	154.0	140.9	147.5	6.5
63	0.62	0.60	0.52	156.6	135.7	146.2	10.4
64	0.63	0.60	0.51	156.6	133.1	144.9	11.7
65	0.64	0.60	0.52	156.6	135.7	146.2	10.4
66	0.65	0.60	0.50	156.6	130.5	143.6	13.1
67	0.66	0.58	0.50	151.4	130.5	140.9	10.4
68	0.67	0.55	0.51	143.6	133.1	138.3	5.2
69	0.68	0.55	0.51	143.6	133.1	138.3	5.2
70	0.69	0.55	0.50	143.6	130.5	137.0	6.5
71	0.70	0.58	0.50	151.4	130.5	140.9	10.4
72	0.71	0.55	0.50	143.6	130.5	137.0	6.5
73	0.72	0.55	0.50	143.6	130.5	137.0	6.5
74	0.73	0.54	0.50	140.9	130.5	135.7	5.2
75	0.74	0.58	0.50	151.4	130.5	140.9	10.4
76	0.75	0.55	0.50	143.6	130.5	137.0	6.5

77	0.76	0.55	0.50	143.6	130.5	137.0	6.5
78	0.77	0.55	0.50	143.6	130.5	137.0	6.5
79	0.78	0.54	0.50	140.9	130.5	135.7	5.2
80	0.79	0.54	0.50	140.9	130.5	135.7	5.2
81	0.80	0.50	0.50	130.5	130.5	130.5	0.0
82	0.81	0.50	0.50	130.5	130.5	130.5	0.0
83	0.82	0.50	0.50	130.5	130.5	130.5	0.0
84	0.83	0.50	0.50	130.5	130.5	130.5	0.0
85	0.84	0.50	0.50	130.5	130.5	130.5	0.0
86	0.85	0.50	0.50	130.5	130.5	130.5	0.0
87	0.86	0.50	0.50	130.5	130.5	130.5	0.0
88	0.87	0.50	0.50	130.5	130.5	130.5	0.0
89	0.88	0.50	0.50	130.5	130.5	130.5	0.0
90	0.89	0.50	0.50	130.5	130.5	130.5	0.0
91	0.90	0.50	0.50	130.5	130.5	130.5	0.0
92	0.91	0.50	0.50	130.5	130.5	130.5	0.0
93	0.92	0.50	0.50	130.5	130.5	130.5	0.0
94	0.93	0.50	0.50	130.5	130.5	130.5	0.0
95	0.94	0.50	0.50	130.5	130.5	130.5	0.0
96	0.95	0.50	0.50	130.5	130.5	130.5	0.0
97	0.96	0.50	0.50	130.5	130.5	130.5	0.0
98	0.97	0.50	0.50	130.5	130.5	130.5	0.0
99	0.98	0.50	0.50	130.5	130.5	130.5	0.0
100	0.99	0.50	0.50	130.5	130.5	130.5	0.0
101	1.00	0.50	0.50	130.5	130.5	130.5	0.0

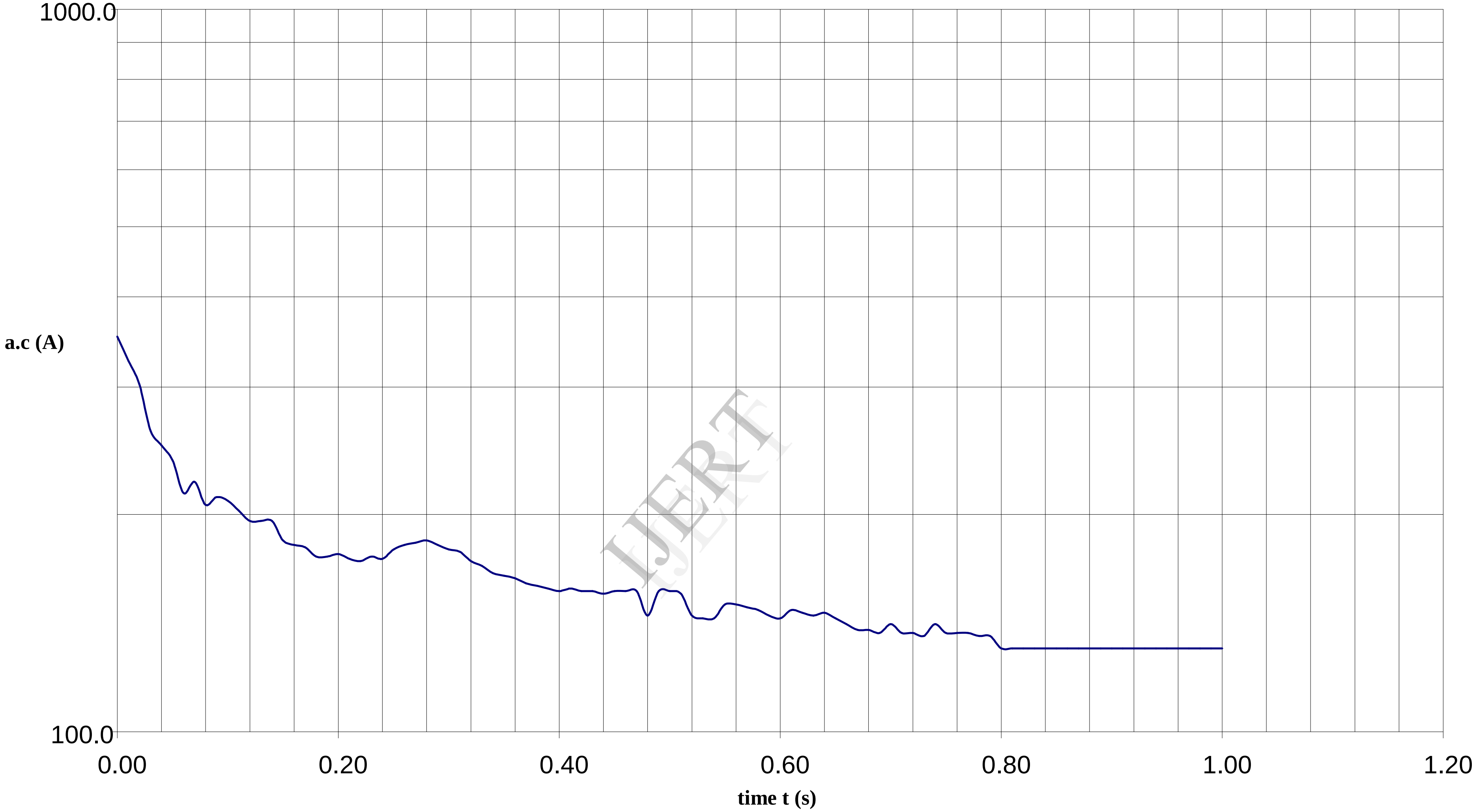

Fig 1: A.C graph

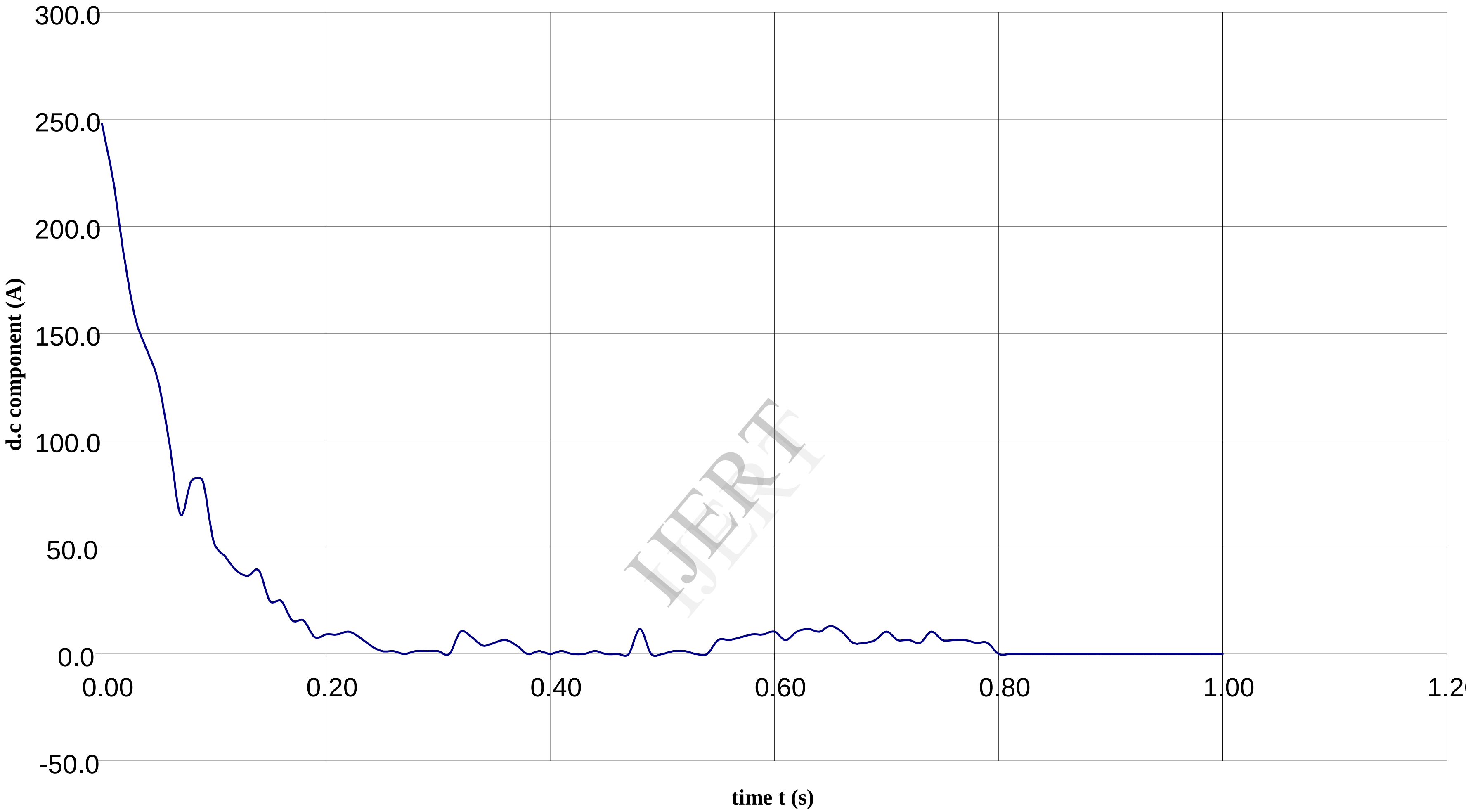

Fig 2: DC GRAPH