PSPICE MODEL OF AN OPEN-CIRCUIT DC SHUNT MACHINE

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Computer models are used to replicate the essential performance features of a physical element using convenient modelling and simulation programs. Within SPICE, an acronym for the Simulation Program with Integrated-Circuit Emphasis, a model for the twin-dependence of the machine's open circuit generated e.m.f. on the time-dependent flux and machine speed has not been investigated. This paper describes a steady-state model of an open circuit DC shunt machine using PSPICE, the PC-version of SPICE packaged within the OrCAD programming environment. The model is based on a characterisation of the generated e.m.f. as a field-current dependent polynomial voltage source whose coefficients are generated within MATHCAD by applying a linear regression fit on a set of experimental laboratory data points. The simulation results are displayed using the inbuilt graphic postprocessor within PSPICE called PROBE. These results show good replicative model validity within the laboratory range of exciting currents used in the simulation

1 PROBLEM IDENTIFICATION

The programs in this paper were implemented using the student version of PSPICE within OrCAD, a programming environment whose predecessor was MicroSim DesignLab.

The problem at hand is primarily to simulate the open-circuit performance of a DC shunt machine. This shall be achieved by modelling the value of the generated e.m.f. as the flux is varied at constant-speed as well as the speed is varied at a constant level of excitation. We expect that if the simulation were valid, the model used would be able to reproduce the well-known inner magnetisation characteristic of the shunt machine's self-excitation process.

In the following sections we set out to define a proposed model, simulate it, and establish its replicative validity. Thereafter we use an example to illustrate the potential suitability of the model for further DC shunt machine experiments.

2 DC MACHINE TERMINOLOGY

The constructional details [1] of a simple $2p$-pole DC machine comprise essentially of an armature rotating at a speed N rev./min within a properly designed uniform air-gap across which a useful flux of Φ Weber per pole-pair p of the machine exists.

The armature is made up of a total of Z conductors. These conductors are conveniently grouped into C parallel paths. In each path a total of Z/C conductors are connected in series, so as to produce a machine with desired electrical characteristics. An armature wound in lap for instance has as many parallel groups of conductors, C as there is number of poles. This results in a machine with a higher current and lower voltage output than a similarly rated machine of the same total number of conductors but wound in wave. In general the number of parallel paths in a DC machine is given by:

$$C = 2p \qquad \text{(1)}$$

where $p = 1$ for a wave-wound armature.

The type of machine is dictated by the manner in which the field winding(s) is (are) connected vis-à-vis the armature terminals m, k shown in Figure1. The figure shows a machine referred to as being compound-connected due to the existence of both the series-field winding R_s and the shunt-field winding R_f. Further, the machine is long-shunted because the shunt-winding is made across the entire armature and the series-field winding.

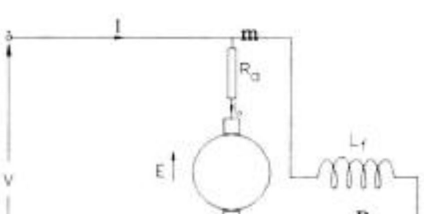

Fig.1. Long shunt compound-connected DC machine

In the absence of the series-field winding, the shunt-field winding is connected effectively across the armature terminals m, and results in a set of simpler terminal equations as given in (7) – (9). The application of basic Faraday's law of Electromagnetic Induction to the rotary motion of the armature conductors results in the induced E.m.f., E where:

$$E \alpha \phi . N \qquad (2)$$

This can be shown to reduce to,

$$E = \frac{2pNZ\phi}{60C} \qquad (3)$$

Furthermore, the application of Ampere's law to an armature carrying a current I_a, results in a generated torque T, proportional to I_a thus:

$$T \alpha \phi . I_a \qquad (4)$$

Given the rotary mechanical power, P where

$$P = \frac{2pNT}{60} \qquad (5)$$

and equating the electrical power input, $E.I_a$ at the machine air-gap to the mechanical power one obtains the explicit torque relation:

$$T = \frac{pZ\phi . I_a}{\pi C} \qquad (6)$$

in which p, N, Z, Φ, I_a and C are respectively, the number of pole-pairs, the speed in rev./min, the total number of active conductors, the useful flux per pole, the armature current and the number of parallel paths determined by whether the armature is lap- or wave-wound. The set of equations (4)-(6) has been included to provide a reference when considering related DC machine characteristics.

The application of Kirchhoff's laws to Fig.1 results in the following terminal equations for the DC shunt machine:

$$E = V \pm I_a R_a \qquad (7)$$

$$V = I_f R_f \qquad (8)$$

$$I_a = I \pm I_f \qquad (9)$$

where V is the terminal voltage, R_a and R_f are respectively the armature and field winding resistance, I and I_f respectively the load and field current and the sign + and - stand respectively for the generating and motoring modes of the machine.

3 THE GENERATED E.M.F. MODEL

We seek for a model that can simulate the electrical machine shown in Fig.1 given equation (3) and the constraints in form of equations (7) – (9). A PSPICE model of the circuit in Fig.1 requires an exact representation of the rotational e.m.f. E. Recognising that E is a function of the field current during the process of self-excitation; it is plausible to model E as a current-dependent voltage source. Towards this end, the open-circuit characteristic data of the DC Machine was first obtained from a laboratory experiment as shown in Fig. 2.

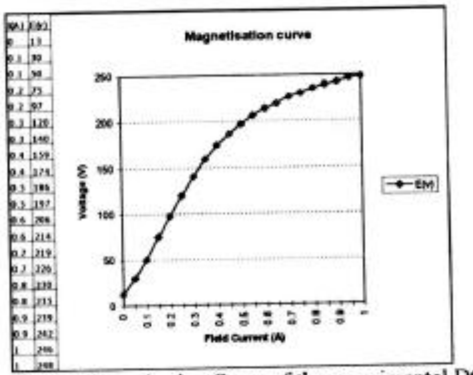

Fig. 2 Magnetisation Curve of the experimental DC Electric machine

Evidently, the relationship between E and the field current is non-linear due to saturation effects. We elect to model this non-linearity by assuming that a polynomial function $E(I_f)$ of yet unknown order exists between the generated e.m.f., E and the field current I_f thus:

$$E(I_f) = \sum_{i=0}^{n} C_i (I_f)^i \qquad (10)$$

where C_i are the polynomial coefficients. In PSPICE, the description of the current-dependent polynomial voltage source E shall therefore require the explicit specification of the coefficients, C_i in terms of their value and correct field position in the syntax description of E within PSPICE. We will employ the experimental curve to generate the coefficients. For this purpose, a few pivotal points on the curve were selected for use in formulating a system of non-linear equations in I_f about the pivots:

$$E_i = \sum_{i=0}^{n}\sum_{j=0}^{n} C_j.(I_f)_i^j \text{..............................}(11)$$

The coefficients C_j in this system of equations were solved for using MATHCAD [2].

3.1 EXPERIMENTAL DATA

In this section we reproduce the vectorial representation of the experimental data as entered in MATHCAD and summarise the essential programming steps required to produce a linear regression fit on the data. Vx is a vector representing the independent variable I_f, and Vy represents the generated e.m.f. data obtained during the open-circuit test. S is a vector of coefficients resulting from a linear regression fit on the experimental curve.

These vectors are given as follows:

$$vx := \begin{bmatrix} 0.000 \\ 0.03442 \\ 0.0977 \\ 0.15107 \\ 0.20718 \\ 0.26608 \\ 0.33474 \\ 0.4076 \\ 0.51724 \\ 0.70625 \\ 1.02382 \\ 1.50687 \\ 2.50376 \\ 4.16016 \\ 8.96718 \end{bmatrix} \qquad vy := \begin{bmatrix} 13.0 \\ 25 \\ 50 \\ 75 \\ 100 \\ 125 \\ 150 \\ 175 \\ 200 \\ 225 \\ 250 \\ 275 \\ 300 \\ 325 \\ 344.1 \end{bmatrix}$$

The set of data points (vy_j, vx_j) represents the experimental curve. The set of points (g, r) represents the resulting approximation to the experimental curve using the linear regression coefficient vector, S indicated below:

Given the vector F(x), where

$$F(x) := \begin{bmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \\ x^4 \\ x^5 \\ x^6 \end{bmatrix}$$

then in MATHCAD, $S := \text{linfit}(vx, vy, F)$ and the approximating vector g(t) is obtained from F(t(thus:

$r := 0, 0.05 .. 10$

$g(t) := F(t)\cdot S$

Figure 3 shows conveniently two curves for easy of comparison.

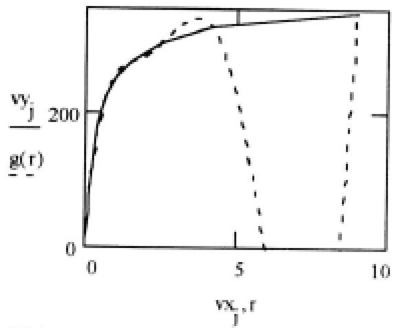

Fig. 3 Linear regression fit on the experimental data

Using the set of x-values shown by vector F above, it is evident from the given graph that the simulation curve approximates closely the experimental curve only at low values of current. The simulation curve diverges failing to reproduce the experimental data at higher values of the field current. Vector S below shows the set of coefficients pertaining to figure 3.

$$S = \begin{bmatrix} 5.768 \\ 563.703 \\ -477.08 \\ 198.661 \\ -40.011 \\ 3.631 \\ -0.118 \end{bmatrix}$$

Were this set of coefficients to be adopted in the ensuing description of the polynomial voltage source E, the validity of the model obtained would be limited to those field-current values within the linear part of the graph. However such a low range of field current is impractical considering the operating conditions of the actual machine. A quest for an improved range of field currents for which the model would still be valid was therefore in order. It was observed that by increasing the power n of the radix I_f increases the number of coefficients used in the simulation and that this in turn had a dramatic effect on the shape of the resultant simulation curve. The comparison of the curves obtained during intermediate simulation trials revealed that there was a progressive tendency for the curve to converge. Eventually at n = 7, the coefficients as output by the vector S_f are those shown as follows:

$$S_f = \begin{bmatrix} 13.06 \\ 515.8 \\ -417.2 \\ 180.8 \\ -43.62 \\ 5.876 \\ -0.4132 \\ 0.01181 \end{bmatrix}$$

These were therefore adopted in the final polynomial description of the current-controlled polynomial voltage source.

4 SPEED-MULTIPLICATION MODEL

The circuit diagram in Fig.1 was modified as shown in Fig. 5 for implementation on PSPICE. The figure shows not only a rearrangement of the circuit elements appearing in Fig.1, but also a sub-circuit, as seen to the right of the axis a-a', that is designed to model the open-circuit characteristic at multiples of the base speed.

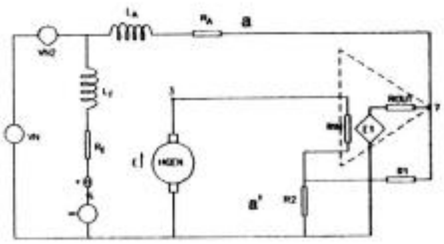

Fig. 4. PSPICE circuit to simulate the DC machine

The sub-circuit shown dotted in fig 4 and reproduced in Fig. 5 consists of an operational amplifier acting as a multiplier circuit using resistor R_2 and the feedback resistor R_1 to determine the amplification factor [3-4].

Fig. 5 Multiplier sub-circuit

The output voltage at node 7 is related to the voltage at the input port thus:

$$V_o = AV_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where,

$$A = \frac{R_1 + R_2}{R_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

An appropriate choice of a fixed value for resistance R_2 together with a judicious parametric variation of resistance R_1 within PSPICE, enables the sub-circuit to give a voltage output at node 7 that is a multiple replica of its base value at node 3. The multiplication factors correspond thereby to multiples of the base speed at which the generated e.m.f. at node 3 was simulated. Alternatively, instead of varying the speed in definite multiples, the user can modify the syntax of the line of code related to the **PARAM** statement in the PSPICE program and specify an arbitrary list of factors by which the speed may be changed.

5 SIMULATION SOURCE CODE

The source code file for this problem was written and it is reproduced below.

```
DC MACHINE O.C. CHARACTERISTICS
*C.S.A.M. Kiravu, Stand/2\OrCAD
*CAPE-SHNT

HGEN 3 0 POLY(1) VN1 13.06 515.8 + -417.2
180.8 -43.62 5.876
+ -0.4132 0.01181
VN1   1    0    DC    0
VN2   4    2    DC    0
VIN   4    0   DC     250
RA    2    7    0.5
RF    2    10    250
*SPEED VARIATION E.G. BY 10%,20%, *30%
40% AND 50% OF NOMINAL VALUE
R1    7    5    RMOD 0.1
.MODEL  RMOD   RES(R=1)
.STEP  LIN   RES   RMOD(R) 1   + 5   1
R2    5    0    1
.SUBCKT        OPMULT        100      200 +
       300    400
RIN   200    100    10000
ROUT   600    300    75
E     600    400    200    +100     10000
.ENDS  OPMULT
XOPMULT  3 5 7       0        OPMULT
.PARAM          IF       1
IF      10      1       DC      1
.DC   IF 0    1   0.05
.PROBE V(3) V(7)
.END
```

6 RESULTS

6.1 THE OPEN-CIRCUIT VOLTAGE

The simulated open-circuit voltage at node 3 is indicated in Fig. 6. This agrees fairly closely with the experimental curve alluded too earlier in Fig.2

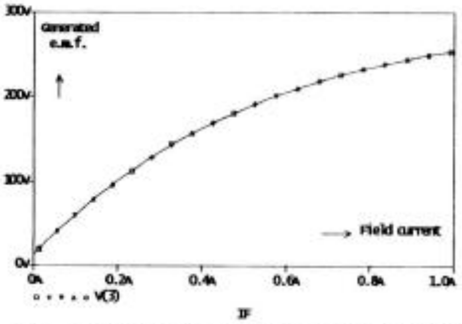

Fig. 6 Simulated curve of the open-circuit voltage

6.2 EFFECT OF INCREASING SPEED

The source file in the PSPICE program changes the speed by 10% of the base speed. Fig. 7 shows the resulting generated e.m.f.s. at various speeds. The curves are shown on the same set of axes as the base simulation curve represented by V (3).

The resulting family of curves for varying speeds agrees fairly closely with the experimental data within the given current range of up to 1A.

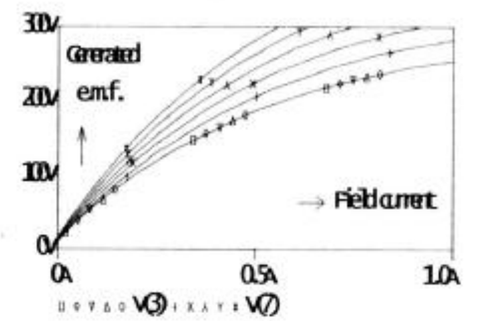

Fig. 7 Effect of speed changes on the simulated open-circuit characteristic

6.3 INCREASING THE RANGE OF VALIDITY

The possible range of field currents for which the simulation model remains valid was next investigated. Fig. 8 and 9 show the corresponding results in conformity with Figs.6 and 7.

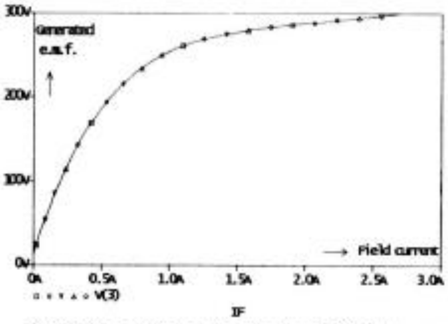

Fig. 8 Generated e.m.f. at extended field current

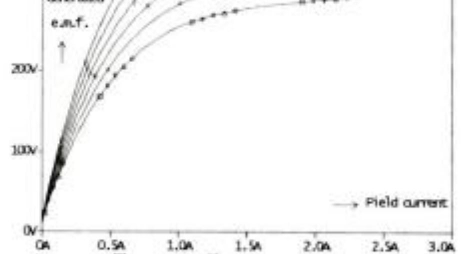

Fig. 9 Effect of speed at extended range currents

7 OTHER TESTS

Students can be guided to attempt various other experiments related to the model for the generated e.m.f. In fact with due consideration to relating theory and practice, students can be made to run such simulation experiments before moving to the elaborate and time-consuming laboratory set-ups involving actual hardware. The following illustrates an example involving the simulation of the load characteristic of a DC shunt generator.

Load characteristic of a DC Shunt generator

DC machine theory predicts, that the DC Shunt-connected generator on-load can be considered to be a practically a constant-voltage machine; its terminal voltage falling linearly from its no-load value V_o to a final value at full-load that is approximately 2%...3% below the no-load value. Using the model for the generated e.m.f, the load characteristic of the shunt machine was investigated. The result is shown in Fig. 10 confirming the theory.

Fig. 10 Terminal voltage versus Load current

In an attempting to vary the activities, the range of investigations can be extended to include other characteristics for instance, the load characteristics of compounded-connected DC generators.

8 CONCLUSION

This paper has expounded a PSPICE model for the generated e.m.f. of a DC shunt machine as a current-dependent polynomial voltage source. The polynomial coefficients were obtained from a set of data points from an actual DC machine by implementing a linear regression fit on the data points using the MATHCAD software package.

The PSPICE source code was generated within the OrCAD environment; but could have as well been implemented within the older MicroSim DesignLab. Apart from being the current design environment for PSPICE, OrCAD presents far decisive advantages over MicroSim. One such advantage is the enhanced capabilities for graphical post-processing within the PROBE software. As an example, the best result one would hope for when embedding a PROBE graph into a word document using MicroSim would be similar to that shown in Fig. 10. Clearly the graph is hardly legible and it required a bit of post-processing for it to print out clearly. For our purposes here though, the graph as it is suffices, because being a straight-line graph, the trend it was intended to reveal is discernible. However, the inclusion of the graph was also intentional in order to bring the contrast between OrCAD and the previous MicroSim clearly to the fore.

The model obtained can be used in other DC machine experiments. Although only one such experiment, the load characteristic of a DC Shunt generator was cited, many others could have been proposed.

At its current status, the model represents a good starting point. Further investigations may be necessary to render the model versatile in dealing with other transient phenomena of the DC machine on-load. The other limitation of the model is that it is machine-specific; being reliant on an experimental curve derived from a named DC Shunt machine. In order to replicate the behaviour of other machines, the specific set of coefficients peculiar to those machines must first be determined. As shown above, and despite the fact that this kind of process is only undergone once, the steps of tuning the polynomial coefficients up to the appropriate final set is cumbersome. Hence a more versatile model that incorporates readily machines of different ratings requires further investigation.

9 REFERENCES

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