MODELLING AND PERFORMANCE STUDY OF SEPARATELY EXCITED D.C. MOTOR FED FROM D.C. CHOPPER USING NUMERICAL TECHNIQUES

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ABSTRACT

The D.C. motor is an attractive piece of equipment in many industrial applications of variable speed and load characteristics, due to its ease of controllability. The speed and performance of the chopper-motor drive is superior in comparison to thyristor controlled bridge-rectifier method.

The objective of this paper is to illustrate how the performance of the D.C. motor can be studied easily using a chopper – drive Modelling and analysis of a complete transformer –rectifier –chopper – D.C. motor system is adopted in this paper using Matlab Simulink as well as numerical technique with Fortran Power Station programing to prove the validity of the analysis.

Keyword: DC motor, chopper, GTO thyrestor, performance Characteristics.

1 INTRODUCTION

Standard separately excited D .C. motors are classified as either constant speed or adjustable speed motors. Adjustable speed motors may be operated over a wide speed range by controlling the armature voltage [1].

For the last thirty years , the development of various solid state switching devices in the thyristor families along with varieties of analog / digital chips used in firing circuits of the thyristor, has made an impact in the area of D .C. drives. These power electronic controllers are of two types[2] :
1-Thyristor bridge rectifiers (converters supplied from A.C supply ).
2- Chopper-drives fed from D.C supply.

The chopper driver method has the following advantages over thyristor bridge rectifiers method [1,2,3]:
1- High energy efficiency
2- Flexibility in control
3- Quick response
4- Light weight and compact control unit.
5- Less ripple in the armature current.
6- Small discontinuous conduction region improves the speed regulation and transient response of the drive.
7- Ability to control down to very low speed.

The aim of this work was to implement a complete modelling and performance study of D.C. motor fed from Y-Y step down transformer- uncontrolled 3-phase bridge rectifier-gate turn-OFF thyristor chopper. The analysis of the complete system was implemented by two methods:

I. **MATLAB SIMULINK**

II. **COMPUTER PROGRAMING USING RUNGE –KUTTA NUMERICAL TECHNIQUE AND FORTRAN –POWER STATION LANGUAGE METHOD**

2 **SCHEMATIC DIAGRAM OF THE SYSTEM**

The complete schematic diagram of the transformer –uncontrolled rectifier- chopper- D.C. motor system was shown in figure (1). The complete system diagram was built with blocks from the library of power system in Matlab combined with Simulink blocks. The complete blocks diagram of the Mat Lab Simulink was shown in figure (2).

3 **THE BASIC CHOPPER CIRCUIT**

The basic chopper circuit, often referred to as class 'A' chopper was shown in figure (1). This form of chopper connection was sometimes called "buck" or "step-down" converter, because the output voltage cannot exceed the input voltage level [2,3].

The chopper switch in earlier days was a thyristor, which requires a forced commutation to turn it OFF. Nowadays, a gate – turn – OFF (GTO) thyristor was used, which can be turned – OFF through its gate. The action of the D.C. chopper was to apply a train of unidirectional voltage pulses to the armature winding of the D.C. motor as shown in figure (3).

By varying the duty ratio ($\gamma$), the average armature voltage ($V_a$) can be controlled as:

$$V_a = \gamma V_m \quad \text{---------- (1)}$$
Where $\gamma = \frac{T_{ON}}{T_c}$ = duty ratio of the chopper.

$V_m$ was the net average output voltage of the uncontrolled bridge rectifier as shown in figure (4).

$T_c$ = the period of one – chopping cycle

$T_{ON}$ = the ON – period in one – chopping cycle.

Also the chopping frequency ($F_c$) was given as:

$$F_c = \frac{1}{T_c} = \frac{1}{T_{ON} + T_{OFF}} \quad (2)$$

Where $T_{OFF}$ was the OFF – period in every chopping cycle.

4 MODELLING THE D.C. MOTOR

The motor block diagram was shown in figure (2). The load torque applied to the motor shaft can be selected as a constant value or a step function. The D.C. motor was represented by Simulink model of the D.C. machine. The motor block was modeled in two separate parts, electrical and mechanical.

- The armature circuit was represented by a resistive-inductive circuit ($R_a$ - $L_a$) in series with a controlled voltage source, the value of which was ($K_m \cdot w$). Where ($K_m$) was the motor constant (N.m /A), and ($w$) was the motor speed in radian / second.

- The field circuit of the motor was represented by resistive-inductive circuit ($R_f - L_f$).

- The mechanical part was represented by Simulink blocks, which implement the following equation:

$$T_m = J \frac{dw}{dt} + B \cdot w + T_L \quad \text{(3)}$$

Where $T_m$ was the mechanical torque (N.m).

$J$ was the motor moment of inertia (kg.m²)

$B$ was the friction torque coefficient

$N.m / (\text{rad} \cdot \text{sec}.)$

$T_L$ was the load torque applied to the motor shaft.

- A smoothing inductor with (0.4) H inductance ($L_{sm}$) and (2.0) $\Omega$ resistance ($R_{sm}$) was connected in series with the D.C. motor to smooth out the armature current.

- The required triggering signal for the GTO thyristor –chopper was generated by a pulse generator.

- The motor supply voltage ($V_m$) was taken as the net average output voltage of the 3-phase bridge diode-rectifier.

- The reduction voltage in the output of the rectifier due to the overlap was taken into account.

- The rectifier was fed from 3 – phase star-star connected, step – down (400 / 170)v transformer. The specifications of D.C. motor, transformer and the rectifier were given in the appendix.
5 D.C. EQUIVALENT CIRCUIT OF THE SYSTEM

For the purpose of formulation of machine equations, the chopper operation was assumed to be an ideal switch. Figure (4.a) shows the per phase equivalent circuit of the transformer referred to the secondary side. Due to both rectification and chopping processes, the transformer secondary current ($I_s$) was no longer sinusoidal [1]. If the chopper frequency was high or the smoothing inductor was large, then the rectified current ($I_d$) was essentially a D.C with negligible superimposed ripple. Thus the transformer secondary current was approximately composed of alternating square pulses of $\frac{2\pi}{3}$ duration[1]. The average rectified current ($I_d$) was related to transformer secondary current ($I_s$) by:

$$I_s^2 = 2I_d^2 / 3.$$ \hspace{1cm} (4)

Due to the leakage reactance's of the transformer ($x_p'$ and $x_s$), the commutation of current between diodes in the rectifier was no longer instantaneous. The reduction voltage ($V_r$) from the output terminals of the rectifier was given by [2]:

$$V_r = 3.(X_p' +X_s).I_d / \pi.$$ \hspace{1cm} (5)

The power loss in the primary and secondary resistance ($R_p'$ and $R_s$) of the transformer for all 3-phases was $[3I_s^2 (R_p' +R_s)]$ or equal to $[2I_d^2 (R_p' +R_s)]$ if expressed in terms of the D.C. current.

Hence, the term $3(R_p' +R_s)$ transferred across the rectifier bridge, appears as $2(R_p' +R_s)$ in the D.C. side.

If the magnetizing current was not specifically required and the diode drops were neglected, the system can be represented by the D.C. equivalent circuit as shown in figure (4.b).

The output voltage of the bridge rectifier ($V_d$) was given as [1]:

$$V_d = 3\sqrt{6} \cdot E_p' / \pi.$$ \hspace{1cm} (6)

Where $E_p' = (V_L / \sqrt{3}) / (N_p / N_s)$ the primary (r.m.s) phase voltage of the transformer referred to the secondary side.

$V_L$ was the primary (r.m.s) line voltage of A.C. supply ($N_p / N_s$) was the primary to secondary turns ratio per phase.
6 MODELLING OF THE CHOPPER –MOTOR SYSTEM

From the D.C .equivalent circuit of the hole system in figure ( 4 . b ) , a set of equations for ON and OFF modes of chopper operation can be derived . In the period that starts at \( M T_c \) [ M being a dummy variable in figure ( 3 ) ] , the chopper was ON for \( MT_c \leq t \leq (M + \gamma ) T_c \) and OFF for :

\( (M + \gamma ) T_c \leq t \leq (M + 1) T_c \).

let the current flowing during the ON and OFF mode be \( i_{ON} (t) \) and \( i_{OFF} (t) \) respectively. The equation of these currents were :

-During ON – period \( (MT_c \leq t \leq (M + \gamma ) T_c ) \) :

\[
\frac{di_{ON}(t)}{dt} + \frac{1}{\tau_{ON}} i_{ON}(t) = \frac{(V_d-K_m \cdot w)}{(L_{sm}+L_a)} \quad \text{or}
\]

\[
\frac{dK_m}{dt} = \frac{1}{(L_{sm}+L_a)} \left[ V_d - \left( R_m + R_a \right) i_{ON} - K_m \cdot w \right]
\]

Where

\[
\tau_{ON} = \frac{(L_{sm}+L_a)}{(R_m+R_a)} \quad \text{The system time constant during ON – period}
\]

\( R_m = \left\{ \left( \frac{\phi_p^2 + x_s}{\pi} + 2 (R_p^2 + R_s) + R_{sm} \right) \right\}
\]

was the transformer – rectifier – smoothing inductor equivalent resistance .

-During OFF – period \( (M + \gamma ) T_c \leq t \leq (M+1) T_c \) :

\[
\frac{di_{OFF}(t)}{dt} + \frac{1}{\tau_{OFF}} i_{OFF}(t) = -\frac{K_m \cdot w}{L_a}
\]
\[
\frac{di_{OFF(t)}}{dt} = \frac{1}{L_a} \left( -R_a i_{OFF(t)} - K_m W \right) \quad \text{---(8)}
\]

Where

\[
\tau_{OFF} = \frac{L_a}{R_a} \quad \text{OFF-period (freewheeling period)}
\]

time constant of the motor circuit.

The motor speed during ON and OFF periods can be determined as:

- During ON-period

\[
\frac{dw}{dt} = \frac{1}{J} \left( K_m i_{ON(t)} - BW - T_L \right) \quad \text{---(9)}
\]

- During OFF-period

\[
\frac{dw}{dt} = \frac{1}{J} \left( K_m i_{OFF(t)} - BW - T_L \right) \quad \text{---(10)}
\]

The sets of linear differential equations were solved numerically by fourth–order Runge–Kutta method. The method has high accuracy if the size of the incremental step of calculation was extremely small, but this increases the processing time [4].

The system parameters were given as input data, computation starts with initial conditions of motor current and speed. The new values were calculated at each step. At each step the chopper was tested whether in ON-period or OFF-period. In ON-period equation (7) and (9) were solved numerically, while in OFF-period equation (8) and (10) were solved. The instantaneous mechanical developed torque on the motor shaft was given as:

\[
T_m = K_m i_a \quad \text{---(11)}
\]

Where \(i_a\) = instantaneous armature current

7 RESULTS

The performance characteristics during transient as well as steady–state operation of the D.C motor fed by GTO thyristor chopper were studied. The effect of source impedance (overlap phenomenon) on the output voltage of the rectifier and the effect of smoothing inductor on the motor operation were considered. The analysis and modeling were done in two methods:

1- Matlab / Simulink was built using advanced blocks from power system block set library. The power system blocks were suitable for preliminary verification of control
system, as A.C. components of current and switching phenomena of diodes and thyristor-chopper were not neglected [5,6].

The results of starting-up and steady-state conditions of D.C. motor were shown in figures (5-8). The possibility of discontinuous conduction occurs at low chopping frequency, low duty ratio and light loads.

2- Numerical analysis using Runge-Kutta technique to solve the system differential equations during ON and OFF periods of chopper operation. Fortran Power Station language was used to implement the system equations. The results of this method were compared with that of Matlab modeling to prove the validity of both methods in the complete system analysis.

Figures (9-11) show the starting-up conditions without load at high and low duty ratios and chopping frequency. Figure (12) shows the steady-state condition with a load torque (5) N.m applied at the motor shaft. From the comparison with the Matlab/Simulink result there was a close agreement between the two methods.

8 CONCLUSIONS

The transformer-rectifier-chopper-D.C. motor system model was implemented in two methods: Matlab/Simulink blocks using power system block set and numerical analysis using fourth-order Runge-Kutta technique. The transient as well as steady-state loading conditions can be studied easily in these methods. From the results, the discontinuous operation of D.C. motor can be occurred in case of low duty ratio, low chopping frequency and light loads.

9 REFERENCES

6- "power system block set user's guide" TEQSIM International Inc. ' 1998.

10 Appendix

A. D.C. motor specifications
The D.C. machine has the following parameters:
- Armature input voltage = 220 V
- Motor rated power = 1.2 Kw
- Field voltage = 220 Volts
- Field resistance = 370 Ω
- Field inductance = 6.4 H
- Armature resistance = 4 Ω
- Armature inductance = 0.086 H
- Moment of inertia = 0.017 Kg.m²
- Friction torque constant = 0.0081 (N.m) / (rad/sec)

B. Transformer specifications
The transformer is 3-phase, two-windings with the following parameters:
- Connection = Y → Y
- Rated power = 15 KVA
- Primary resistance = 1.2 Ω
- Secondary resistance = 0.5 Ω
- Primary leakage reactance = 0.3 Ω
- Secondary leakage reactance = 0.1 Ω
- Magnetizing resistance = 2000 Ω
- Magnetizing reactance = 1500 Ω

C. Bridge rectifier specifications
The uncontrolled 3-phase bridge diodes rectifier has the following properties:
- Forward resistance = 0.2 Ω
- Forward voltage drop = 0.6 Volts
- Reverse voltage = 400 Volts
- Snubber resistance = 3 × 10³ Ω
- Snubber capacitance = 0.01 × 10⁻⁶ Farad

D. Thyristor chopper specifications
The thyristor chopper has the following properties:
- Forward resistance = 0.001 Ω
- Forward voltage drop = 0.8 V
- Snubber resistance = 10 Ω
- Snubber capacitance = 4.7 × 10⁻⁶ Farad
- Turn-off time = 100 × 10⁻⁶ Second
Figure (4) simplified steady state equivalent circuit of the system

Figure (5) Matlab results for starting-up condition
(F_0=50 Hz, T=0, \gamma=0.5)
Figure (7) Matlab results for steady-state condition
($f_o=200$ Hz, $T_i=0$ N.m., $\gamma=0.99$)

Figure (8) Matlab results for steady-state condition
($f_o=50$ Hz, $T_i=0$ N.m., $\gamma=0.5$)
Figure (8) Matlab results for steady-state condition
\( f_r = 50 \text{ Hz}, T_e = 5.0 \text{ N.m, } \gamma = 0.99 \)

Figure (9) FORTRAN results for starting-up condition
\( f_r = 50 \text{ Hz, } T_e = 0 \text{ N.m, } \gamma = 0.5 \)
Figure (11) FORTRAN results for steady-state condition
($F_r=200$ Hz, $T_i=0$ N.m., $\gamma=0.99$)