DYNAMIC ANALYSIS AND SPEED CONTROL OF AC-DC ZETA CONVERTER FED DC MOTOR

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ABSTRACT

A simplified approach for speed control of a separately excited DC motor using single-phase, single-way rectifier is presented in this paper. The strategy of this approach is based on the cascade combination of a diode bridge rectifier and a Zeta converter. The power factor is near unity. The output voltage and current are smooth with ripple free. A high performance is achieved with a simple control circuit having only one switch for the converter. The analysis predicts the steady-state, run-up and dynamic behaviors of the proposed system in different modes of operation is presented. The IP controller parameters are selected from an overview of practical experience so that it satisfies the best required response for load and speed reference disturbances. Good agreement between experimental and simulated results has been observed, which supports the validity of the proposed analysis.

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Keywords: Separately excited DC motor, Closed-loop speed control, AC-to–DC converter.

1. INTRODUCTION

The power supplies suffer from current distortion and low power factor operation. This is due to employing a conventional single-phase voltage source diode rectifier with a filter capacitor at the output terminal and also the phase controlled rectifiers using thyristors. In order to overcome these disadvantages, various circuit topologies using power switching devices, such as Gate Turn Off Thyristors, Power Transistors, MOSFET'S. and IGBT'S AC-to-DC converters have been implemented and obtain high power factor and minimum current distortion with static loads [1-7].

The advantages of using power electronic technology in electric device systems became doubtless fact, especially with the rapid and continuous increase in device ratings and speeds. However, power supplies of such systems suffer from current distortion and low power factor. These undesirable effects have motivated the international standard organization to impose restrictions on the magnitude of harmonic contents in the line currents of the switched mode power supplies. Although the problem of low power factor can be solved by adding power factor correction (PFC) equipments, such a solution may still be undesirable in terms of size, weight and cost [8].

Electronic power processing technology commonly is known as pulse-width modulation (PWM). The PWM technique processes power by controlling the duty cycle and interrupting the power flow, but results in pulsating voltage and current. Due to control easily and circuit simplicity, the PWM technique has been used predominantly in low power application. With circuit technologies, PWM converters have been designed to operate with a 30-50 KHz switching frequency. In this frequency range, the equipment is deemed optimal in size, cost, efficiency, weight and reliability. Through this study, no attention has been paid to the transient performance of DC motor when supplied from the proposed converter [9-11].

In this paper, a simple AC-to-DC zeta converter feeding a separately excited DC motor is presented. This technique is performed without using a current sensor but only a simple control circuit with step-up/down capability is used. This converter yields an approximately unity power factor, in addition, the motor voltage and current are nearly ripple free.

The digital simulation for open and closed loop speed control system is given. The proposed experimental system is used to compute the best controller parameters for transient responses. Although the load was disturbed within the range ±50% of its rated value, the motor speed appears to be consistent and

remain constant. Also, the speed response due to a step change in the reference speed is fast with a reasonable overshoot. Finally, the simulation results are in good agreement when compared with the experimental values.

2. DESCRIBTION OF THE EXPERIMENTAL SYSTEM

Figure (1) shows the schematic diagram of the complete control system for speed control. The system consists of a cascade combination of a single-phase diode bridge rectifier and a zeta converter connected to AC single-phase supply. Step-up and step-down behavior of the output voltage is obtained by regulating the control voltage (V_c) from 0 to maximum value (A) of the timing voltage (W_a) shown in Figure (2). This technique has been used to control the motor speed. Capacitor C_1 supplies energy to L_2. The capacitor C_2 is used as a DC filter to obtain smooth and ripple free output DC voltage.

The MOSFET is fired by an impulse generator having leaner timing voltage. The gate pulses are generated

such that the control voltage (V_c) equals the timing voltage (W_a) as shown in Figure (2). Control of motor speed is performed using integral proportional (IP) controller. The switching frequency (f_s) is set to 2 KHz.

The parameters of the power circuit are determined according to the range of the switching frequency and acceptable percentage of the output ripple. The rate of change of i_1, switching frequency and value of C_1 are determined by the value of L1. The resonant frequency is given by $f_r = (1/2\pi)(L_1 C)^{0.5}$ and should be sufficiently lower than the switching frequency $f_s = 1/T$ to prevent any resonant phenomenon in the AC circuit. The corner frequency of the low-pass filter is selected to be much lower than the switching frequency, thus essentially eliminating the switching frequency ripple in the output voltage. The higher values of L_2 and C_2 assign the better output voltage and current but on the expense of the system time response. The parameters values of the designed system are given in Appendices.
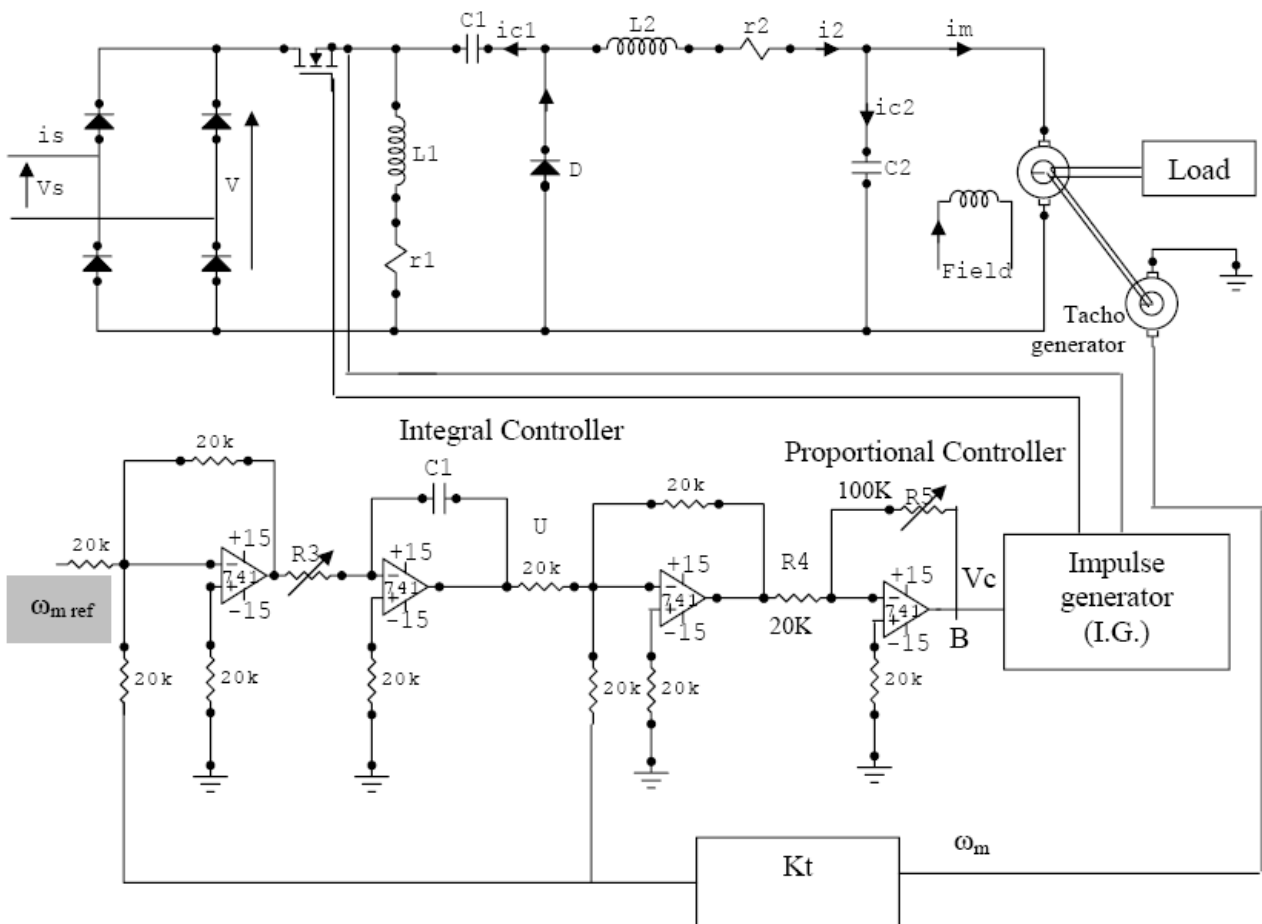

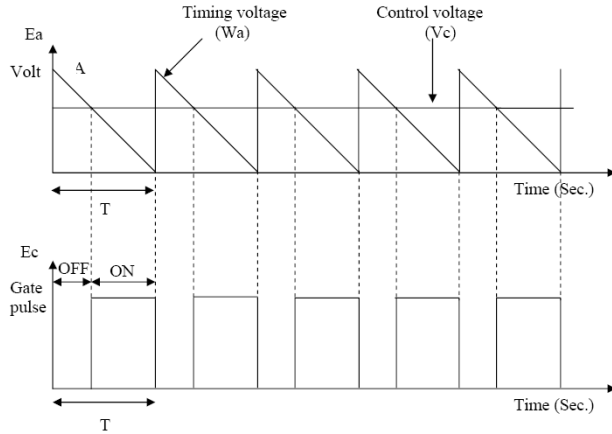**Figure 1.** Schematic diagram of the experimental system

Figure 2. Output of the drive and control circuit

3. SYSTEM MODELING AND MODES OF OPERATIONS:

A step-up and down of the output voltage can be obtained by regulating the duty ratio, where:

Duty ratio $K = T_{on}/T$ (1)

Where T_{on} is the switch on time.
T is the switch (on + off) time.

The motor is separately excited DC motor. The load is separately excited DC generator. The switching frequency is given by:

$$f_s = 1/T \qquad (2)$$

The motor parameters are given in Appendix 3.

There are three modes of operation. Such modes of operation may be explained in the following sections.

3.1. Mode (1)

In this mode the MOSFET is on and the diode is off, while the MOSFET is conducting the line source supply energy to inductor L_1. The energy available in inductor L_2 comes from line source and capacitor C_1. The currents i_{L1} and i_{L2} increase. Voltages V_m and e are considered constant and equal to load voltage. The differential equations describing this mode are:

$$\frac{di_1}{dt} = \frac{v - r_1 i_1}{L_1} \qquad (3)$$

where: $v = V|\sin \omega t|$

$$\frac{de}{dt} = \frac{i_s - i_1}{C_1} \qquad (4)$$

$$\frac{di_m}{dt} = \frac{v_m - r_m i_m - k_m \omega_m}{L_m} \qquad (5)$$

$$\frac{d\omega_m}{dt} = \frac{K_m i_m - B\omega_m - T_L}{J} \qquad (6)$$

$$\frac{dv_m}{dt} = \frac{i_2 - i_m}{C_2} \qquad (7)$$

$$\frac{di_2}{dt} = \frac{v - v_m - i_2 r_2 + e}{L_2} \qquad (8)$$

$$i_s = i_1 + i_2 \qquad (9)$$

$$i_D = 0 \qquad (10)$$

3.2. Mode (2)

In this mode the MOSFET is off while the diode is on. The MOSFET is turned off and the diode starts to conduct, the energy from L_1 and L_2 is transferred to C_1 and C_2 respectively. In mode (2) there is no energy circulation in the line, which assures that there is no any harmonic distortion in the current. The differential equations describing this mode may be written as:

$$\frac{di_1}{dt} = \frac{-i_1 r_1 + e}{L_1} \qquad (11)$$

$$\frac{de}{dt} = \frac{-i_1}{C_1} \qquad (12)$$

$$\frac{di_m}{dt} = \frac{v_m - r_m i_m - k_m \omega_m}{L_m} \qquad (13)$$

$$\frac{d\omega_m}{dt} = \frac{K_m i_m - B\omega_m - T_L}{J} \qquad (14)$$

$$\frac{dv_m}{dt} = \frac{i_2 - i_m}{C_2} \qquad (15)$$

$$\frac{di_2}{dt} = \frac{-i_2 r_2 + v_m}{L_2} \qquad (16)$$

$$i_s = 0 \ , \ i_D = i_1 + i_2 \qquad (17)$$

3.3. Mode (3)

In this mode both MOSEFT and the diode are off. When the current i_{L1} and i_{L2} become equal, the diode turns off and starts the mode (3). The voltage applied in the inductances L_1 and L_2 are zero and their currents are constant until MOSFET is able to conduct, restarting the operation cycle. The differential equations describing this mode are:

$$\frac{di_m}{dt} = \frac{v_m - r_m i_m - k_m \omega_m}{L_m} \qquad (18)$$

$$\frac{d\omega_m}{dt} = \frac{K_m i_m - B\omega_m - T_L}{J} \qquad (19)$$

$$\frac{dv_m}{dt} = \frac{-i_m}{C_2} \qquad (20)$$

$$i_s = 0 \ , \ i_D = 0 \ , \ i_1 = 0 \qquad (21)$$

3.4. Modeling of the Drive Circuit

The saw tooth carrier signal (W_a) is given by the following equation:

$$Wa = A\left[1 - X/T\right] \qquad (22)$$

Where: $T = 1/f_s$, $\quad$ f_s is the switching frequency,

$\quad$ X is the instant of the intersection in radians,

and $\quad$ A is the peak value of the carrier voltage.

If the control voltage V_c is greater than W_a then the MOSFET is on, but if the V_c is smaller than W_a then the MOSFET is off.

3.5. Controller Equations:

The controller equations are given by:

$$\tau\left(dU/dt\right) = \omega_{mRef} - K_t \omega_m \qquad (23)$$

$$Vc = K_1\left(U - K_t \omega_m\right) \qquad (24)$$

Where K_1 and τ_1 are the IP speed controller parameters.

4. STEADY STATE CHARACTERISTICS

Figure (3) shows the effect of varying duty ratio on speed and power factor at 0.25 and 0.5 full-load conditions.
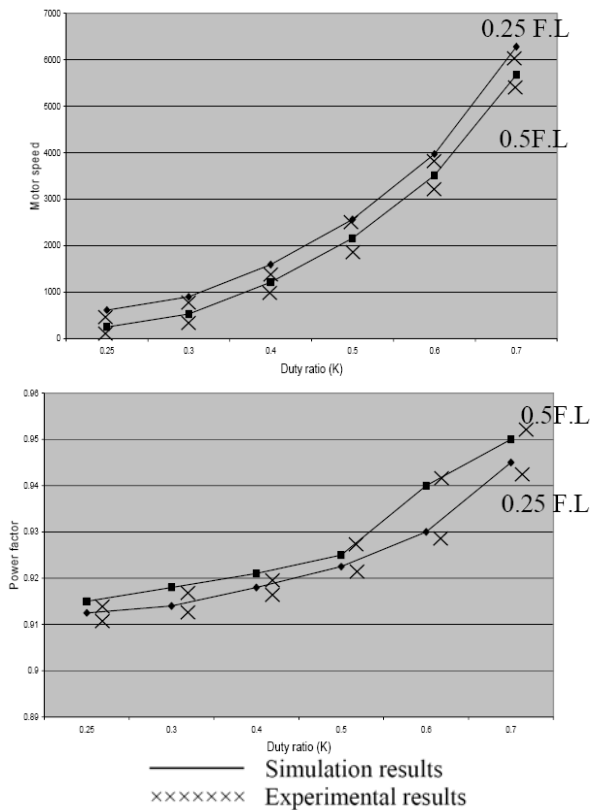
Figure (3) Effect of duty ratio on the steady-state characteristics

5. CLOSED LOOP SPEED CONTROL OPERATION

In reference [12-13], it is shown both theoretically and experimentally, that integral proportional controller (IP) offers good advantages over conventional (PI) controller. The transfer function can be obtained from the simulation results for different loads.

The system transfer function may take the following form:

$$\frac{\omega_m\left(s\right)}{V_c\left(s\right)} = \frac{K_s}{1 + \tau_s s} \qquad (25)$$

Where K_s and τ_s are shown in Appendix 3.

The open loop transfer function of the system shown in figure (1) is given by:

$$\frac{\omega_m\left(s\right)}{\omega_{mref}\left(s\right)} = \frac{K_1 K_s K_t}{\left(\tau_1 s\right)\left(1 + \tau_s s\right)} \qquad (26)$$

For the system to be stable, the cross-over frequency ω_{co} for a phase margin more than 45° is found to be equal to the following equation:

$$\omega_{co} = K_1 K_s K_t / \tau_1 \qquad (27)$$

This method of designing and calculating the speed controller parameters (K_1, τ_1) has the advantage of being straight-forward, simple and accurate. The speed controller parameters are given in Appendix 3.

5.1. Simulation and Experimental Results

Figure (4) shows the variation of motor speed due to positive and negative change in load within ±50% of the motor existing load. It is observed that the speed is returned to its initial value.

Figure (5) shows the positive and negative step change in reference voltage [$\omega_{mref}(s)$] at half full load.

It is observed that the motor speed can follow the desired speed reference smoothly with a reasonable over shoot.

6- CONCLUSIONS

This paper has presented mathematical models by which the performance of a separately excited DC motor fed from AC- DC zeta converter may be successfully predicted.

The proposed control circuit for this system has been achieved nearly unity power factor. Moreover, the DC motor voltage and current were appeared to be ripple free and smooth.

The dynamic and steady-state behaviors were predicted using the proposed analysis. Further, the obtained experimental results may be used to determine the suitable IP speed controller's parameters for closed loop speed control. However, the best responses for load and speed reference disturbances could be obtained.

The speed controller's parameters were predicted for a constant speed operation when the load changes within ±50% of the motor existing load. The motor speed can follow the desired speed reference smoothly and fast with reasonable overshoot.

A good agreement between the simulation and experimental results for open and closed loop systems was found.
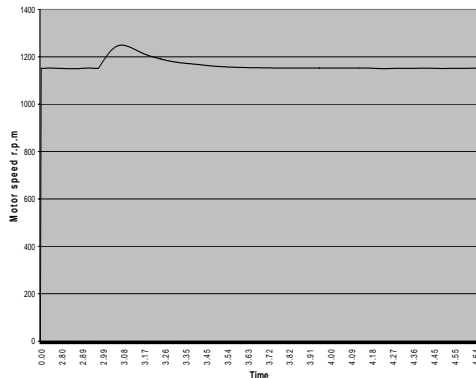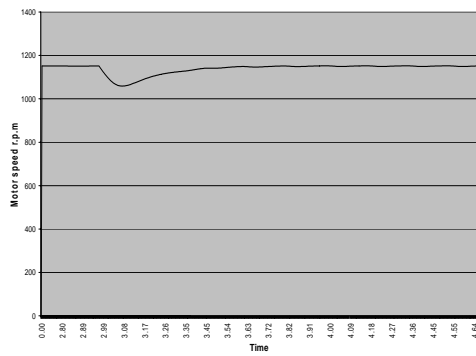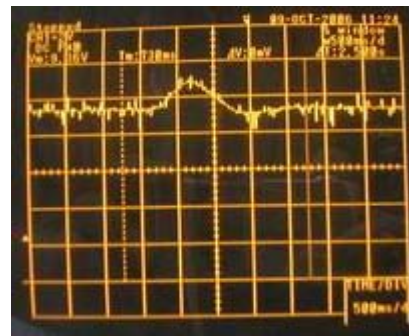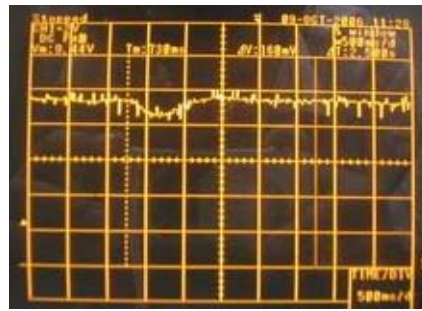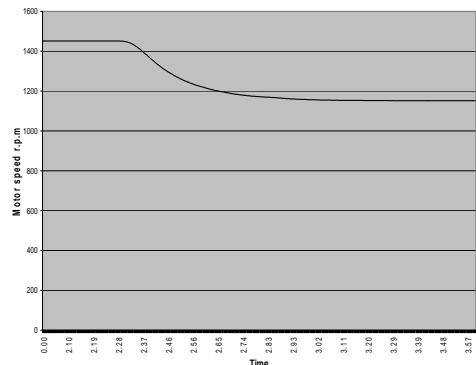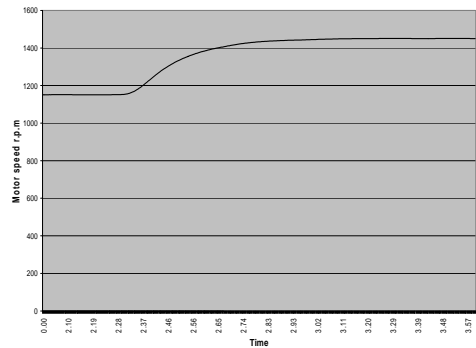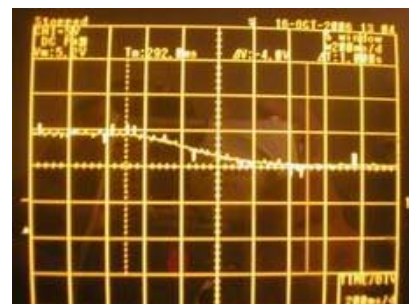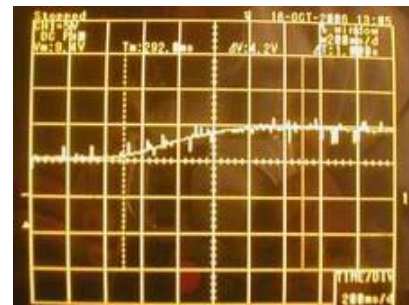
a) Simulation   b) Experimental

Figure (4) Variation of speed due to positive and negative change in load torque
Samples of the steady-state waveforms at 0.5 full load and K=0.5

a) Simulation   b) Experimental

Figure (5) Variation of speed due to positive and negative step change in reference
voltage at half full load

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8. APPENDICES

Appendix (1)

The parameters of the designed system are as follows:

V_s = 50 volt $\qquad$ L_1 = 30 mH $\qquad$ r_1 = 1.5 ohm
C_1 = 15 µf $\qquad$ L_2 = 30 mH $\qquad$ r_2 = 1.5 ohm
C_2 = 2200 µf $\qquad$ A = 12 volt

Appendix (2)

The values of IP speed controller parameters are as follows:

R_3 = 40 KΩ $\qquad$ R_4 = 30 KΩ $\qquad$ R_5 = 30 KΩ
C_3 = 3.3 µf $\qquad$ ω_{mref} =2.89 volt
K_t = 0.019 volt/rad/sec $\qquad$ K_s = 10
K_1 = 1 $\qquad$ τ_1 = 0.14 sec $\qquad$ τ_s = 0.09 sec

Appendix (3)

The test motor is a separately excited DC motor, 50 volt , 55 watt, 1 ampere, 3000 rpm having the following measured parameters:

R_a = 10.5 ohm $\qquad$ L_m = 0.06 H $\qquad$ R_f = 550 ohm
B = 0.0001 N.m./(rad/sec)
K_m = 0.127 Volt/(rad/sec)
J = 0.0012 kg.m^2