CHAPTER 2

ZCS-QRC FED DC MOTOR

2.1 GENERAL

The speed of a DC motor can be controlled by varying the average value of the armature voltage. The same is achieved using a frequency modulated ZCS-QRC. This chapter deals with the analysis, simulation and implementation of a ZCS-QRC fed DC motor system. The comparison of voltage commutated chopper and QRC fed DC drive systems is discussed in order to bring out the advantages of the latter.

A full-wave mode ZCS converter differs from that of the half-wave case in that it has an antiparallel diode across the transistor. The QRCs can be operated in the half-wave and full-wave modes depending upon the connection of the antiparallel diode. The power circuit, various stages of operation and relevant waveforms of half-wave FM-ZCS-QRC are given in Figs 2.1a, 2.1b and 2.1c respectively. The power circuit, stages of operation and relevant waveforms of full-wave FM-ZCS-QRC are shown in Figs 2.2a, 2.2b and 2.2c respectively.

The operation of QRC in the different regions can be fully explored using a single state plane diagram. The state plane plot gives information about the rating of power devices. The state plane plots of HW and FW ZCS-QRCs are shown in Figs 2.3a and 2.3b respectively.

Zero current switching can also be obtained by connecting resonant capacitor in parallel with the series combination of resonant inductor and
Fig. 2.1 Half-wave ZCS-QRC

a Power circuit
b Stages of operation
c Waveforms
Fig. 2.2 Full-wave ZCS-QRC

a Power circuit
b Stages of operation
c Waveforms
Fig. 2.3 State plane plots
a Half-wave QRC
b Full-wave QRC
switch. The resonant converter with this connection is called ZCS resonant switch DC-DC converter. DC drive fed from this converter is discussed in the next chapter. The analysis of ZCS-QRC is presented here.

2.2 ANALYSIS

A switching cycle can be divided into four stages. The associated equivalent circuits and waveforms for these four stages are shown in Figs. 2.1b and 2.1c respectively. Armature inductance of the DC motor is much larger than resonant inductance ($L_a = 200 \mu H$, $L_r = 33 mH$). The DC motor operating at constant load torque is represented as a constant current sink ($I_a$) for analysing the operational modes of ZCS-QRC. Ideal semiconductor switches and reactive elements of the tank circuit are considered for analysing the behaviour of half-wave ZCS-QRC fed DC motor.

To start with, it is assumed that the freewheeling diode $D_{fw}$ conducts and carries the steady state armature current $I_a$, $v_a$ is zero and then the transistor is switched on.

2.2.1 Inductor charging stage ($t_u$, $t_1$)

At the beginning of switching cycle, $t=t_u$, the transistor is on. The entire input voltage $E$ appears across $L_r$ and the current $i_r$ builds up linearly until it equals $I_a$ at $t_1$. The current $i_r$ is governed by the equation

$$L_r (di_r/dt) = E$$

(2.1)

The duration of this stage is obtained as

$$t_{10} = t_1 - t_u = L_r I_a/E$$

(2.2)
2.2.2 Resonant stage ($t_1$, $t_2$)

This stage starts when the current in $L_r$ increases to $I_s$. Thus at $t_1$, $D_{pw}$ is commutated. The current through inductance increases further and the difference between $i_{tr}$ and $I_s$ flows through $C_r$. The voltage across $C_r$ builds up and the corresponding equations are

$$C_r \frac{dv_{cr}}{dt} = i_{tr}(t) - I_s$$

(2.3)

$$L_r \frac{di_{tr}}{dt} = E - v_{cr}$$

(2.4)

with the initial conditions $v_{cr}(0) = 0$ and $i_{tr}(0) = I_s$.

On solving (2.3) and (2.4)

$$i_{tr}(t) = \frac{EZ_0}{\omega} \sin \omega t + I_s$$

(2.5)

where $Z_0 = \sqrt{L_r/C_r}$

and $v_{cr} = E (1-\cos \omega t)$

(2.6)

When the capacitor gets charged to $E$, the current $i_{tr}$ reaches its peak value. This stage ends at $t_2$ when the current $i_{tr}$ has fallen to zero. The duration of this stage is obtained as

$$t_{21} = t_2 - t_1 = \frac{\omega}{\omega_s} = \sin^{-1} \left( \frac{Z_0 I_s}{E} \right) / \omega_s$$

(2.7)
2.2.3 Capacitor discharging stage (t₂, t₃)

This stage begins at t₂ when the current through the inductor Lₑ is zero. At t=t₂, transistor is turned off. The capacitor discharges through the load to supply constant load current. Hence, vₑ decreases linearly and reduces to zero at t₃. The corresponding equation during this interval is

\[ Cₑ \frac{dvₑ}{dt} = Iₑ \]  

The duration of stage 3 can be obtained by solving the equation 2.8 with the initial condition \( vₑ (0) = E (1 - \cos \alpha) \).

\[ t₃ = t₂ - \frac{CₑE(1 - \cos \alpha)}{Iₑ} \]  

When capacitor discharges to zero, the load current transfers to the freewheeling diode.

2.2.4 Freewheeling stage (t₄, t₅)

This stage starts with the conduction of the freewheeling diode. The armature current freewheels through Dₚₑ for a period t₄ until transistor is turned on again.

\[ t₄ = t₃ - t₂ = T - t₁₀ - t₂₁ - t₃₂ \]  

where \( T = \text{Switching period} \)

After an interval t₅, during which both iₑ and vₑ are zero, the base drive to the transistor is again applied at t₄ to turn it on. The operation during the next cycle is similar to that of the preceding cycle. By
controlling the freewheeling time \((t_4-t_3)\), the average value of the armature voltage and hence the speed of the DC motor can be controlled.

The operation of full-wave converter differs from that of half-wave converter only in the resonant stage. The current \(i_u\) reverses at the instant \(t_2'\) and continues to flow for a duration \((t_2'-t_4')\) secs.

### 2.3 SIMULATION RESULTS

The PSPICE software package was used to analyse the transient behaviour of the converter system (Palanivel 1992 and Prabhakaran 1993). Simulated waveforms for half-wave and full-wave modes are given in Figs 2.4 and 2.5 respectively. In the simulation, the armature of DC machine was modelled as a series combination of armature resistance, armature inductance and back emf. The mechanical load connected to it was represented using torque - current analogy. From the simulation results, it was observed that the linear discharging period of capacitor decreases as the load current increases in half-wave mode. In full-wave mode, both the duration of reverse current through \(L_r\) and the linear discharging period of capacitor decrease as the load current increases. The switch-on period of semiconductor device of ZCS-QRC is load dependent since the duration of resonant inductor charging stage is a function of armature current. The PSPICE listings for half-wave and full-wave ZCS-QRC systems are given in Appendices 1 and 2 respectively. The circuit models for HW and FW ZCS QRC systems are shown in Figs. A 1.1 and A 2.1 respectively.

### 2.4 EXPERIMENTAL RESULTS

The system analysed above was constructed and thoroughly tested in the laboratory for both the half-wave and the full-wave modes of operations. The experimental setup of ZCS-QRC system is shown in Fig 2.6. The observations with the HW-ZCS-QRC are given in Table 2.1.
Fig. 2.4  Simulation waveforms of HW-QRC
a  Armature voltage
b  Inductor current
Fig. 2.5 Simulation waveforms of FW-QRC

a) Armature voltage
b) Inductor current
Fig. 2.6  Experimental setup of ZCS-QRC system
TABLE 2.1
OBSERVATIONS WITH HW-ZCS-QRC SYSTEM

<table>
<thead>
<tr>
<th>S.No.</th>
<th>$T_{sw}$ (µ Sec.)</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>935</td>
<td>100</td>
</tr>
<tr>
<td>2.</td>
<td>810</td>
<td>120</td>
</tr>
<tr>
<td>3.</td>
<td>631</td>
<td>170</td>
</tr>
<tr>
<td>4.</td>
<td>396</td>
<td>236</td>
</tr>
<tr>
<td>5.</td>
<td>349</td>
<td>266</td>
</tr>
<tr>
<td>6.</td>
<td>271</td>
<td>340</td>
</tr>
<tr>
<td>7.</td>
<td>209</td>
<td>414</td>
</tr>
<tr>
<td>8.</td>
<td>177</td>
<td>474</td>
</tr>
<tr>
<td>9.</td>
<td>115</td>
<td>602</td>
</tr>
<tr>
<td>10.</td>
<td>60</td>
<td>714</td>
</tr>
<tr>
<td>11.</td>
<td>13</td>
<td>920</td>
</tr>
</tbody>
</table>

Normalised speed versus normalised switching frequency curves for half-wave and full-wave systems are shown in Fig.2.7. The oscillograms of the armature voltage and inductor current for half-wave QRC system with load are shown in Fig.2.8. It is observed that the speed of the machine can be varied from 100 to 920 rpm by varying the freewheeling time from 935 to 13 µs. It can be seen from the oscillograms that transistor does not stop conducting exactly at $t_f$. This may be due to parasitic junction capacitance and reverse recovery of the transistor.

The oscillograms of the armature voltage and inductor current for full-wave QRC system with full load are shown in Fig.2.9. In full-wave mode, the speed of the machine was varied from 60 to 600 rpm by varying the freewheeling time from 900 to 15 µs.
Fig. 2.7 Normalised speed-normalised switching frequency curves
Fig. 2.8 Oscillograms of HW-QRC
   a Armature voltage
   b Inductor current

Fig. 2.9 Oscillograms of FW-QRC
   a Armature voltage
   b Inductor current
It can be noted that for the same switching frequency, speed in full
wave mode is less compared to half-wave mode. Also, the linear region of $v_{cr}$
is less. This enables operation at higher switching frequencies in full-wave
mode. It is noted that the duration of the linear discharging of capacitor
decreases as the load on the motor increases.

2.5 COMPARISON OF QRC AND VCC FED DC DRIVES

Voltage commutated chopper (VCC) operating at 3.7 KHz and HW-
QRC system operating at 6.4 KHz were simulated by modelling the DC
motor as a R-L-E load. The corresponding armature current waveforms of
DC motor operating at 30% of full load are shown in Figs.2.10a and 2.10b
respectively. The armature reactance in the HW-QRC system is high since
QRCs operate at higher frequencies than the hard switched choppers.
Therefore, the armature current ripple gets reduced. The same can be
observed from the armature current waveforms. The PSPICE listing for
VCC system is given in Appendix 3. The circuit model of VCC system is
shown in Fig. A 3.1.

2.6 SUMMARY

This chapter demonstrated the application of ZCS-QRC to control
the speed of a separately excited DC motor drive. The drive system has been
modelled and its behaviour was studied by simulation. A prototype ZCS-
QRC fed DC drive was implemented and found to function satisfactorily over
a wide range of speeds. The experimental results are in close agreement
with simulation results.
Fig. 2.10a  Simulated armature current of VCC system
Fig. 2.10b  Simulated armature current of QRC system