Chapter 3

Proposed fault-tolerant structure for cascaded H-bridge multilevel inverter

Proposed fault-tolerant structure for a 7-level CHBMLI shown in Figure 3.1. Additional 18 relays are used to divert current path during faulty operation. In Figure 3.1; RS1-RS9 are single pole single throw (SPST) relays and RD1-RD9 are single pole double throw (SPDT) relays. When any module gets faulty; operation of CHBMLI remains continue by two actions: (i) Isolation of faulty module and (ii) Connecting the source of faulty module in series with one of the sources of healthy modules. Depending upon how many modules get faulty, operation for FT-CHBMLI can be divided into 3 different modes. Which can be subdivided into 7 different modes as shown in Table 3.1. Different mode of operation has been described in below section.

A	B	C	Operation	
H	H	H	Mode-0	All Modules Healthy
F	H	H	Mode-1	One Module Faulty
H	**F**	H	Mode-2	
H	H	**F**	Mode-3	
F	**F**	H	Mode-4	Two Module Faulty
H	**F**	**F**	Mode-5	
F	H	**F**	Mode-6	

H = Healthy | **F** = Faulty Module

Table 3.1: Operating modes

To disconnect the faulty module/modules and to utilize its sources different relays need to be operated to modify structure of the CHBMLI. Respective relays required to be operated in different modes are shown in Table 3.2. Operation of relays depends upon type of fault and location of fault. When any single module gets faulty, 6 relays are required to be operated to maintain the operation. And during double module fault 9 to 11 relays need to be operated as shown in Table 3.2. It can be observed from the Table 3.2 that, during normal condition when all the modules are healthy, all the relays are remains in rest condition. Operating respective relays during faulty condition as per Table 3.2 modifies the structure of CHBMLI. During normal condition

when all the modules are healthy, three similar DC sources are utilized along with 3 bridge modules forming symmetrical CHBMLI structure.

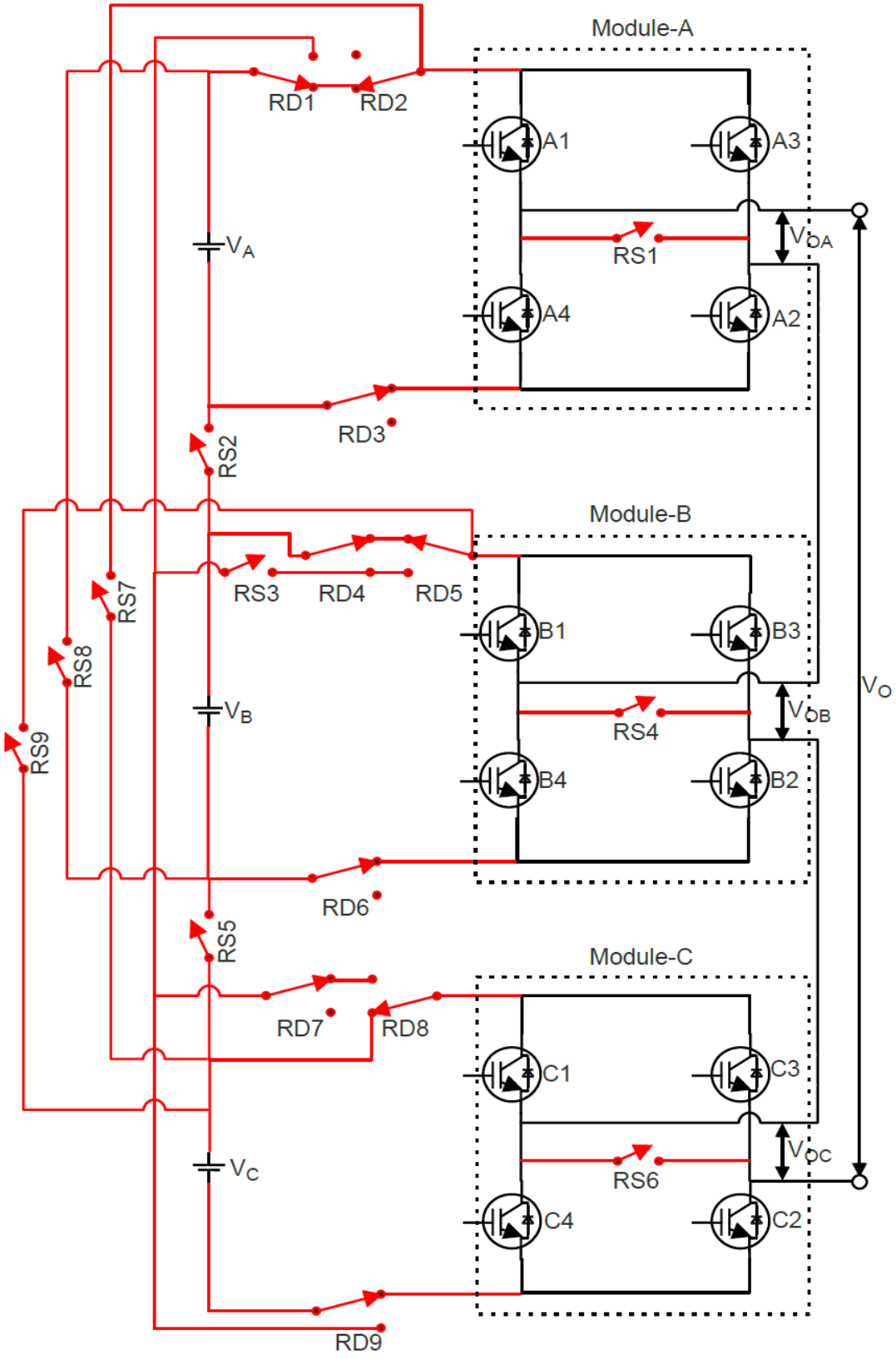

Figure 3.1 Proposed fault-tolerant structure for CHBMLI

During faulty condition if any one module is faulty then DC source of that module is utilized with another DC source of adjacent healthy module. In this manner one bridge module get connected to $2V_{dc}$ while another module continues its operation with V_{dc}. With this kind of asymmetric distribution of DC sources, CHBMLI operate as asymmetric CHBMLI. Further, during double module fault as two out of three module gets faulty, DC sources of faulty module gets connected to remaining healthy module. In this manner single module operate as 3-Level PWM inverter with DC voltage of $3V_{dc}$.

Level Shifted-PWM consist of one sinusoidal reference and six triangular carrier is shown in Figure 3.2 which operates the CHBMLI. PWM Strategy needs to be modified during faulty condition. Gate pulses of faulty module should be retrieved. As the faulty condition change the structure of CHBMLI from symmetrical to asymmetrical and asymmetrical to 3-level, PWM generation strategy should be modified according modified structure.

RELAY	MODE-0 A=H, B=H, C=H	MODE-1 A=F, B=H, C=H	MODE-2 A=H, B=F, C=H	MODE-3 A=H, B=H, C=F	MODE-4 A=F, B=F, C=H	MODE-5 A=H, B=F, C=F	MODE-6 A=F, B=H, C=F
RS1	0	1	0	0	1	0	1
RS2	0	1	0	0	1	0	1
RS3	0	1	1	0	0	1	0
RS4	0	0	1	0	1	1	0
RS5	0	0	1	0	1	0	0
RS6	0	0	0	1	0	1	1
RS7	0	0	0	1	0	1	0
RS8	0	0	0	0	0	1	0
RS9	0	0	0	0	0	0	1
RD1	0	1	0	1	1	0	1
RD2	0	0	0	0	0	1	0
RD3	0	1	0	0	1	0	1
RD4	0	0	1	0	0	1	0
RD5	0	1	0	0	1	0	1
RD6	0	0	1	0	1	1	0
RD7	0	0	0	1	0	1	1
RD8	0	0	1	1	1	1	1
RD9	0	0	0	1	0	1	1
TOTAL	0	6	6	6	9	11	10

RS1-RS9 = SPST Relay | **RD1-RD9** = SPDT Relay

H = Healthy Module | **F** = Faulty Module

1 = Relay Operated | **0** = Not Operated

Table 3.2**:** Switching of relays under various modes

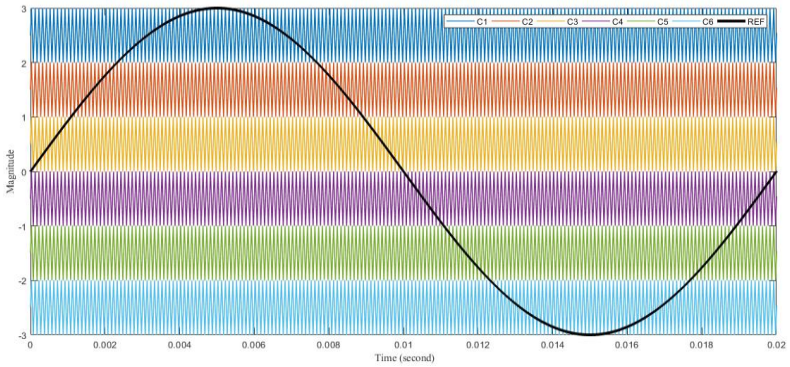

Figure 3.2: Level-shifted PWM (LS-PWM)

Sr.	Condition	State
1	REF > C1	S1
2	C1 ≥ REF > C2	S2
3	C2 ≥ REF > C3	S3
4	C3 ≥ REF > 0	S4
5	0 ≥ REF > C4	S5
6	C4 ≥ REF > C5	S6
7	C5 ≥ REF > C6	S7
8	REF ≤ C6	S8

Table 3.3**:** State selection for IGBT switching

As the CHBMLI changes its operational nature from symmetrical to asymmetrical during faulty condition; state based PWM has been utilized to change modulation strategy of CHBMLI. Phase disposed LS-PWM, using 6 carrier (triangular, C1-C6) and 1 reference (sinusoidal, REF) shown in Figure 3.2 has been utilized to form 8 sectors which indeed represents 7 output voltage levels. Sector segregation as REF travels through C1-C6 has been described in Table 3.3.

3.1 Mode-0: All modules healthy

Seven level symmetrical CHBMLI has 3 similar voltage sources ($V_A = V_B = V_C = V_{dc}$). If all the 3 modules *(A, B & C)* are healthy; then CHBMLI operates under Mode-0 and produces 7-level output voltage (V_O). As all modules are connected in series with appropriate switching, peak voltage $V_{O\,(peak)} = \pm 3V_{dc}$ can be obtained. All the relays in proposed FT-CHBMLI remains in rest condition under Mode-0.

SWITCHING OF IGBT UNDER MODE-0

	Module-A (Healthy)				**Module-B** (Healthy)				**Module-C** (Healthy)				**Voltage**
State ↓	**A1**	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**Level**
S1	1	1	0	0	1	1	0	0	1	1	0	0	+3Vdc
S2	0	1	0	1	1	1	0	0	1	1	0	0	+2Vdc
S3	1	1	0	0	0	1	0	1	0	1	0	1	+Vdc
S4	0	1	0	1	0	1	0	1	0	1	0	1	0
S5	0	1	0	1	0	1	0	1	0	1	0	1	0
S6	0	0	1	1	0	1	0	1	0	1	0	1	-Vdc
S7	0	1	0	1	0	0	1	1	0	0	1	1	-2Vdc
S8	0	0	1	1	0	0	1	1	0	0	1	1	-3Vdc

Table 3.4: Switching of IGBT Under Mode-0

Circuit diagram of FT-CHBMLI has been shown in Figure 3.3. Current flow during Mode-0 has been highlighted. As all of the relays are in rest condition, three DC sources are isolated and connected with 3 bridge modules. Operating this structure as symmetrical CHBMLI provides 7- Level output voltages. Switching of IGBT's in Mode-0 shall be done as per Table 3.4.

3.2 One module faulty; Two modules healthy

If only 1 module *(A or B or C)* is faulty; then CHBMLI operates under Mode-1 or Mode-2 or Mode-3 respectively and produces 7-level output voltage. Table 3.5 represent mode of operation during single module fault. During single module fault respective relays are operated to redirect DC source of faulty module towards healthy module and maintain output voltage same as in healthy condition ($V_{O\ (peak)} = \pm 3V_{dc}$ *(remains same))*. During single module fault 6 relays out of 18 needs to be operated to isolate the faulty module and to utilize its voltage source.

A	**B**	**C**	**Operation**
F	H	H	Mode-1
H	F	H	Mode-2
H	H	F	Mode-3

H = Healthy | **F** = Faulty Module

Table 3.5: One module faulty; Two modules healthy

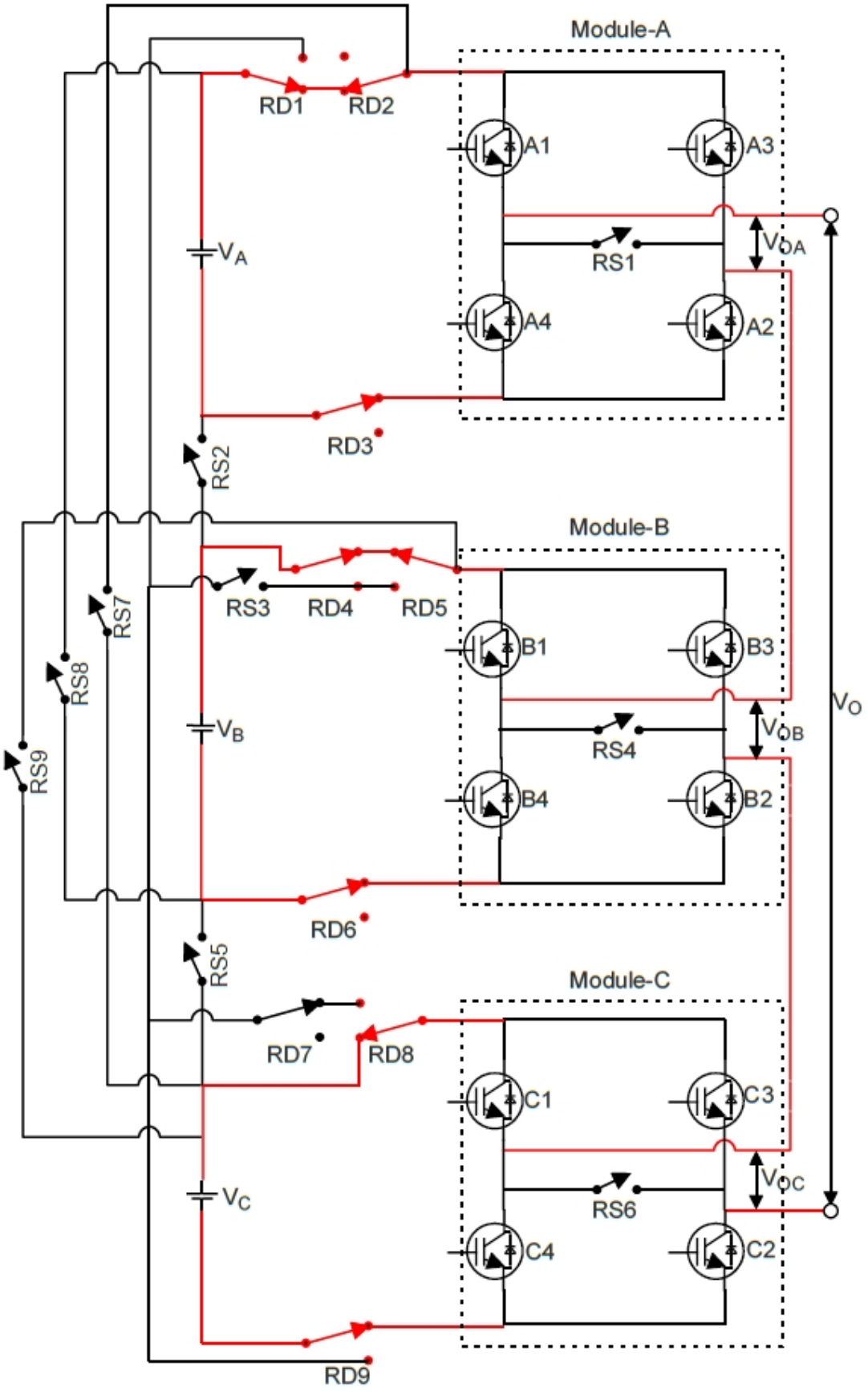

Figure 3.3: Current flow under Mode-0

3.2.1 Mode-1 (Module-A Faulty)

When module A becomes faulty two modules (B & C) remains in operating condition. Modified structure of CHBMLI in Mode-1 is shown in Figure 3.4. RS1 and RD3 are operated to isolate Module-A. Only bypassing the first module and continuing with other two does not provide required output voltage magnitude. To maintain the output voltage RS2, RS3, RD1 and RD5 are operated, which connected source of Module-A in series with the source of Module-B. To generate 7-Level output voltage using Module-B ($2V_{dc}$) & Module-C (V_{dc}), Gate pulses should be modified as shown in Table 3.6.

SWITCHING OF IGBT UNDER MODE-1

	Module-A (Faulty)				Module-B (Healthy)				Module-C (Healthy)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	0	0	0	0	1	1	0	0	1	1	0	0	+3Vdc
S2	0	0	0	0	1	1	0	0	0	1	0	1	+2Vdc
S3	0	0	0	0	0	1	0	1	1	1	0	0	+Vdc
S4	0	0	0	0	0	1	0	1	0	1	0	1	0
S5	0	0	0	0	0	1	0	1	0	1	0	1	0
S6	0	0	0	0	0	1	0	1	0	0	1	1	-Vdc
S7	0	0	0	0	0	0	1	1	1	0	1	0	-2Vdc
S8	0	0	0	0	0	0	1	1	0	0	1	1	-3Vdc

Table 3.6: Switching of IGBT under Mode-1

3.2.2 Mode-2 (Module-B Faulty)

When Module-B becomes faulty two modules (A & C) remains in operating condition. Modified structure of CHBMLI in Mode-2 is shown in Figure 3.5. RS2 and RD6 are operated to isolate Module-B. To maintain the output voltage magnitude same as in healthy condition RS3, RS5, RD4 and RD8 are operated, which connected source of Module-B in series with the source of Module-C. All the operated relays are highlighted in Figure 3.5. To generate 7-Level output voltage using Module-C ($2V_{dc}$) & Module-A (V_{dc}), Gate pulses should be modified as shown in Table 3.7.

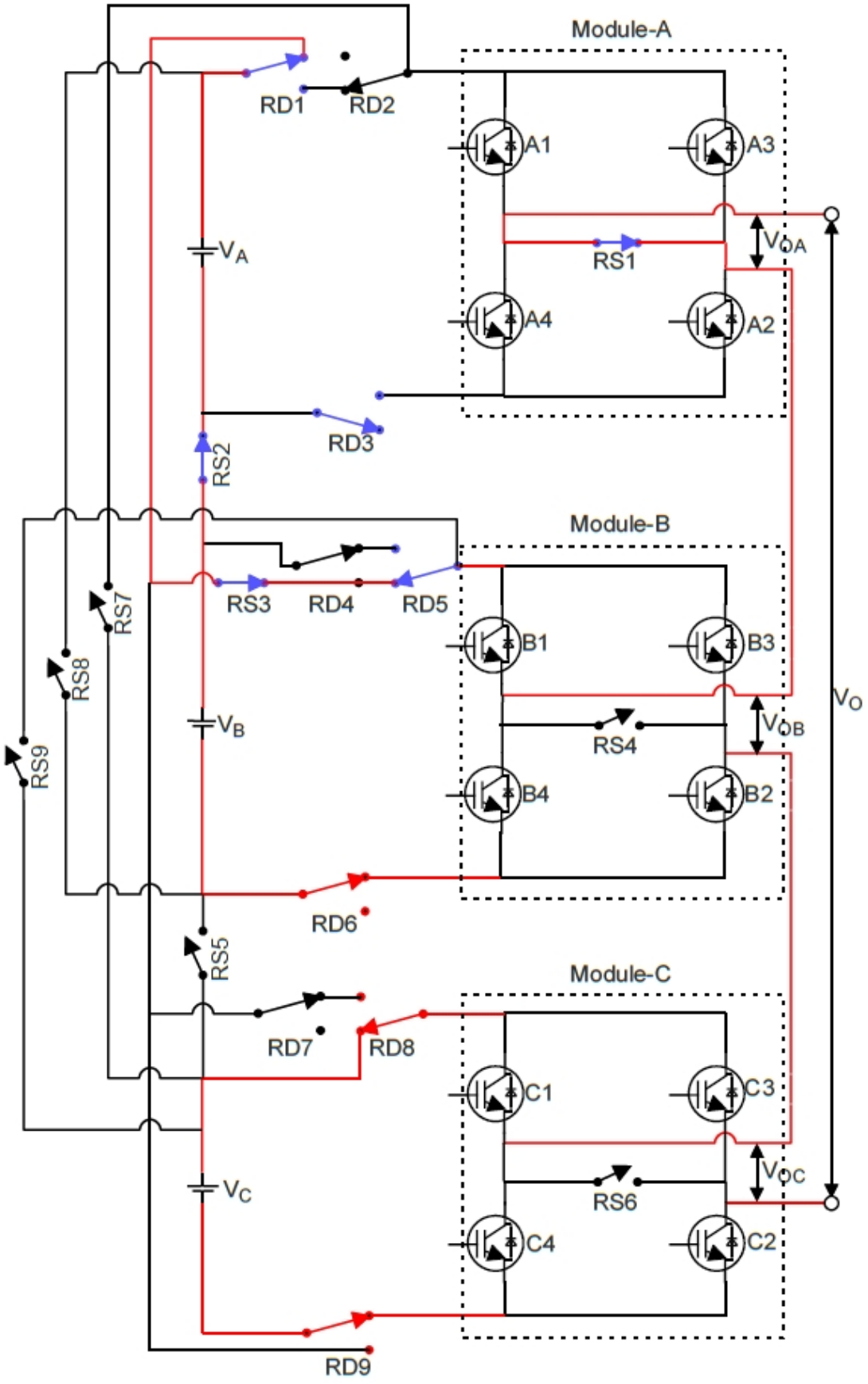

Figure 3.4: Current flow during Mode-1

SWITCHING OF IGBT UNDER MODE-2

	Module-A (Healthy)				Module-B (Faulty)				Module-C (Healthy)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	1	1	0	0	0	0	0	0	1	1	0	0	+3Vdc
S2	1	0	1	0	0	0	0	0	1	1	0	0	+2Vdc
S3	1	1	0	0	0	0	0	0	1	0	1	0	+Vdc
S4	0	1	0	1	0	0	0	0	1	0	1	0	0
S5	0	1	0	1	0	0	0	0	1	0	1	0	0
S6	0	0	1	1	0	0	0	0	1	0	1	0	-Vdc
S7	1	0	1	0	0	0	0	0	0	0	1	1	-2Vdc
S8	0	0	1	1	0	0	0	0	0	0	1	1	-3Vdc

Table 3.7: Switching of IGBT under Mode-2

3.2.3 Mode-3 (Module-C Faulty)

When Module-C becomes faulty two modules (A & B) remains in operating condition. Modified structure of CHBMLI in Mode-3 is shown in Figure 3.6. RS6, RD7 and RD8 are operated to isolate Module-C. To maintain the output voltage magnitude same as in healthy condition RS7, RD1 and RD9 are operated, which connected source of Module-C in series with the source of Module-A. All the operated relays are highlighted in Figure 3.6. To generate 7-Level output voltage using Module-A ($2V_{dc}$) & Module-B (V_{dc}), Gate pulses should be modified as shown in Table 3.8.

SWITCHING OF IGBT UNDER MODE-3

	Module-A (Healthy)				Module-B (Healthy)				Module-C (Faulty)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	1	1	0	0	1	1	0	0	0	0	0	0	+3Vdc
S2	1	1	0	0	1	0	1	0	0	0	0	0	+2Vdc
S3	1	0	1	0	1	1	0	0	0	0	0	0	+Vdc
S4	0	1	0	1	0	1	0	1	0	0	0	0	0
S5	0	1	0	1	0	1	0	1	0	0	0	0	0
S6	0	1	0	1	0	0	1	1	0	0	0	0	-Vdc
S7	0	0	1	1	0	1	0	1	0	0	0	0	-2Vdc
S8	0	0	1	1	0	0	1	1	0	0	0	0	-3Vdc

Table 3.8: Switching of IGBT under Mode-3

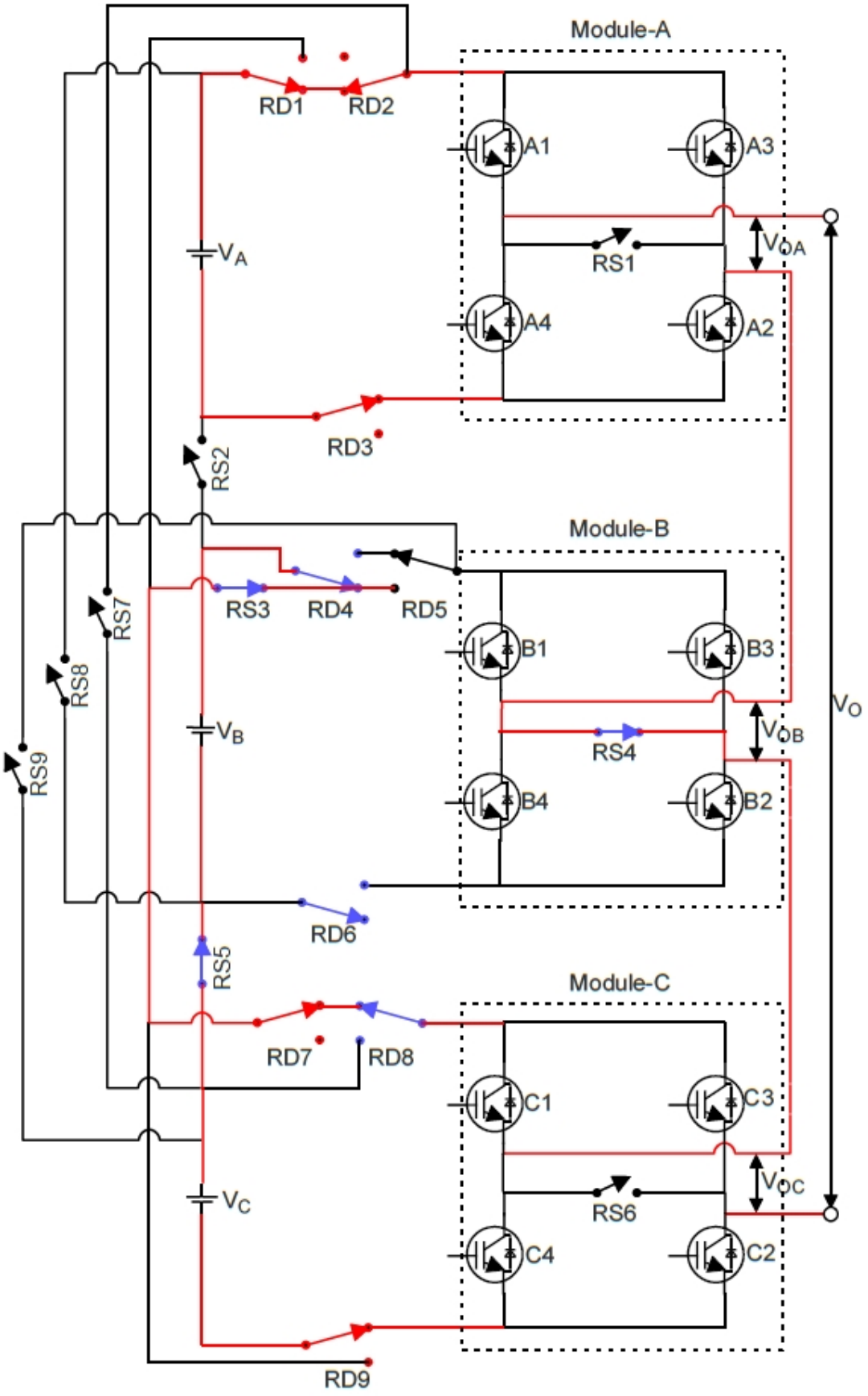

Figure 3.5: Current flow during Mode-2

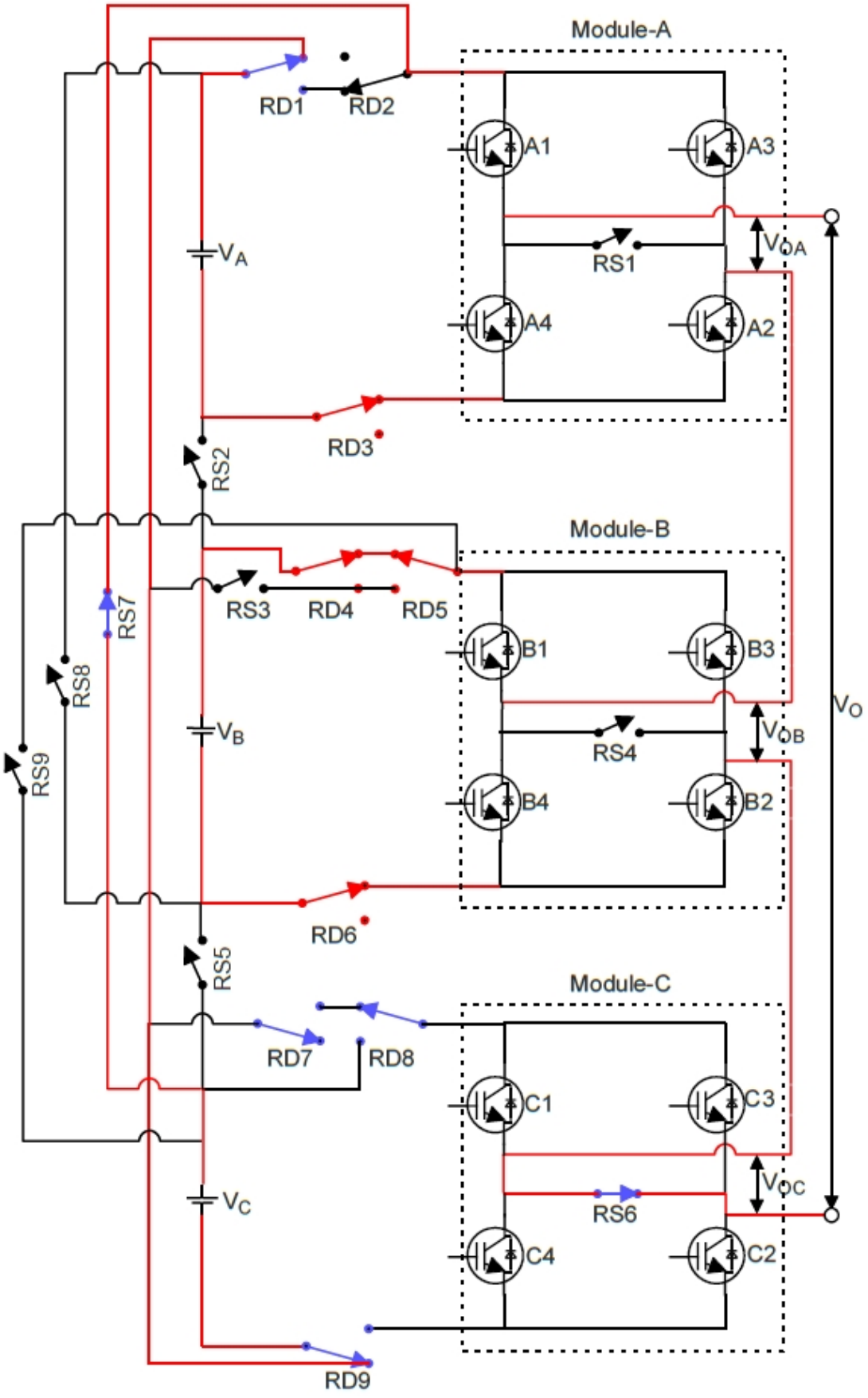

Figure 3.6: Current flow during Mode-3

3.3 Two modules faulty; One module healthy

If only 2 modules *(A&B or B&C or C&A)* is faulty; then CHBMLI operates under Mode-4 or Mode-5 or Mode-6 respectively and produces 3-level output voltage. Table 3.9 represent mode of operation during double module fault. During double module fault respective relays are operated to redirect DC source of two faulty modules towards healthy module and maintain output voltage same as in healthy condition ($V_{O\ (peak)} = \pm 3V_{dc}$ *(remains same)).* During double module fault 9 to 11 relays out of 18 needs to be operated to isolate the faulty module and to utilize its voltage source. LS-PWM should be modified by changing modulation index of sinusoidal reference, as shown in Figure 3.7.

A	B	C	Operation
F	**F**	H	Mode-4
H	**F**	**F**	Mode-5
F	H	**F**	Mode-6

H = Healthy | F = Faulty Module

Table 3.9: Two modules faulty; One module healthy

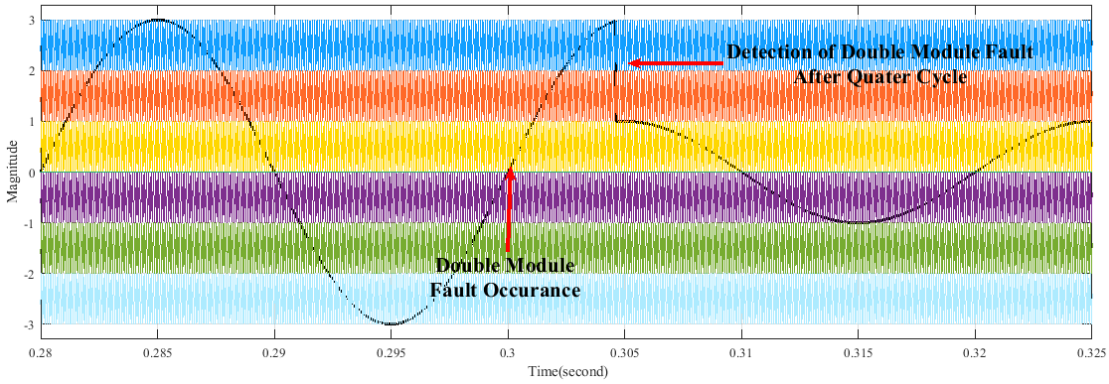

Figure 3.7: LS-PWM for Double Module Fault

3.3.1 Mode-4 (Module-A & Module-B are Faulty)

When Module-A & Module-B becomes faulty Module-C remains in operating condition. Modified structure of CHBMLI in Mode-4 is shown in Figure 3.8. RS1, RD3 and RS4, RD5, RD6 are operated to isolate Module-A and Module-B respectively. To maintain the output voltage magnitude same as in healthy condition sources of Module-A and Module-B utilized along with the source of Module-C. RD1 are operated to

connect source of Module-A to Module-C.RS2 and RS5 are operated to connect voltage sources of Module-C and Module-B in series with Module-A. Series connection of all three sources provide $3V_{dc}$ input voltage to Module-C. All the operated relays are highlighted in Figure 3.8. To generate 3-Level output voltage using Module-C ($3V_{dc}$). Gate pulses should be modified as shown in Table 3.10.

SWITCHING OF IGBT UNDER MODE-4

	Module-A (Faulty)				Module-B (Faulty)				Module-C (Healthy)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	1	1	0	0	+3Vdc
S4	0	0	0	0	0	0	0	0	1	0	1	0	0
S5	0	0	0	0	0	0	0	0	0	1	0	1	0
S6	0	0	0	0	0	0	0	0	0	0	1	1	-3Vdc
S7	0	0	0	0	0	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.10: Switching of IGBT under Mode-4

3.3.2 Mode-5 (Module-B & Module-C are Faulty)

When Module-B & Module-C becomes faulty Module-A remains in operating condition. Modified structure of CHBMLI in Mode-5 is shown in Figure 3.9. RS4, RD6 and RS6, RD7, RD8 are operated to isolate Module-B and Module-C respectively. To maintain the output voltage magnitude same as in healthy condition sources of Module-B and Module-C utilized along with the source of Module-A. RS3, RD4 and RD9 are operated to connect source of Module-B to Module-C. RS8 are operated to connect voltage sources of Module-A in series with Module-B. RS7 is operated to connect source of Module-C with Module-A. Series connection of all three sources provide $3V_{dc}$ input voltage to Module-A. All the operated relays are highlighted in Figure 3.9. To generate 3-Level output voltage using Module-C ($3V_{dc}$). Gate pulses should be modified as shown in Table 3.11.

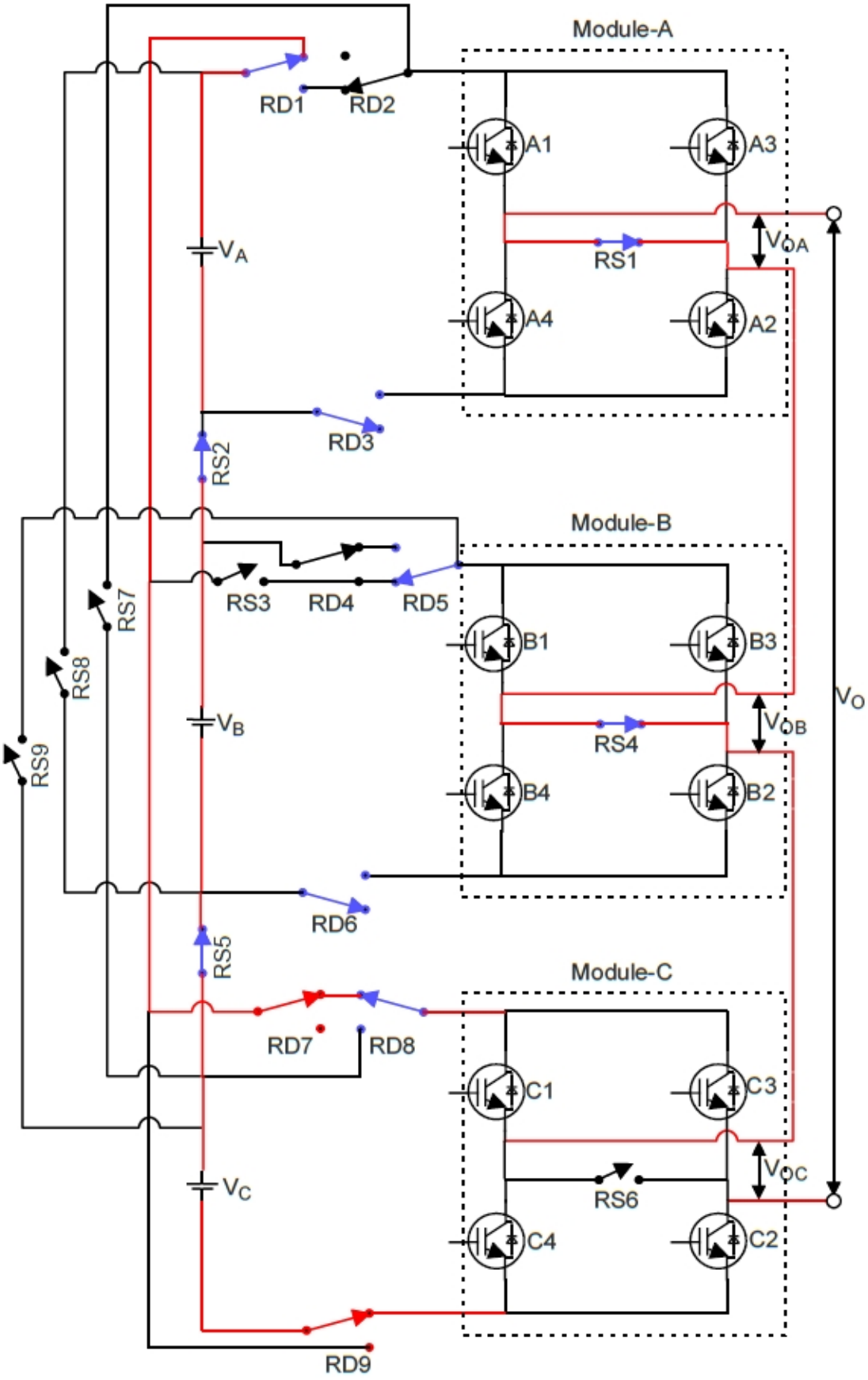

Figure 3.8: Current flow during Mode-4

SWITCHING OF IGBT UNDER MODE-5

	Module-A (Healthy)				Module-B (Faulty)				Module-C (Faulty)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	0
S3	1	1	0	0	0	0	0	0	0	0	0	0	+3Vdc
S4	1	0	1	0	0	0	0	0	0	0	0	0	0
S5	0	1	0	1	0	0	0	0	0	0	0	0	0
S6	0	0	1	1	0	0	0	0	0	0	0	0	-3Vdc
S7	0	0	0	0	0	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.11: Switching of IGBT Under Mode-5

3.3.3 Mode-6 (Module-A & Module-C are Faulty)

When Module-A & Module-C becomes faulty, Module-B remains in operating condition. Modified structure of CHBMLI in Mode-6 is shown in Figure 3.10. RS1, RD3 and RS6, RD7, RD8 are operated to isolate Module-A and Module-C respectively. To maintain the output voltage magnitude same as in healthy condition sources of Module-A and Module-C utilized along with the source of Module-B. RD5 is utilized to isolate source of Module-B and RS2 is operated to connect it with source of Module-A. RD1 and RD9 are operated to connect source of Module-A with source of Module-C. Finally, RS9 connect source of Module-C to Module-B. Series connection of all three sources provide $3V_{dc}$ input voltage to Module-B. All the operated relays are highlighted in Figure 3.10. To generate 3-Level output voltage using Module-C ($3V_{dc}$). Gate pulses should be modified as shown in Table 3.12.

SWITCHING OF IGBT UNDER MODE-6

	Module-A (Faulty)				Module-B (Healthy)				Module-C (Faulty)				Voltage Level
State ↓	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	
S1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	1	1	0	0	0	0	0	0	+3Vdc
S4	0	0	0	0	1	0	1	0	0	0	0	0	0
S5	0	0	0	0	0	1	0	1	0	0	0	0	0
S6	0	0	0	0	0	0	1	1	0	0	0	0	-3Vdc
S7	0	0	0	0	0	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.12: Switching of IGBT Under Mode-6

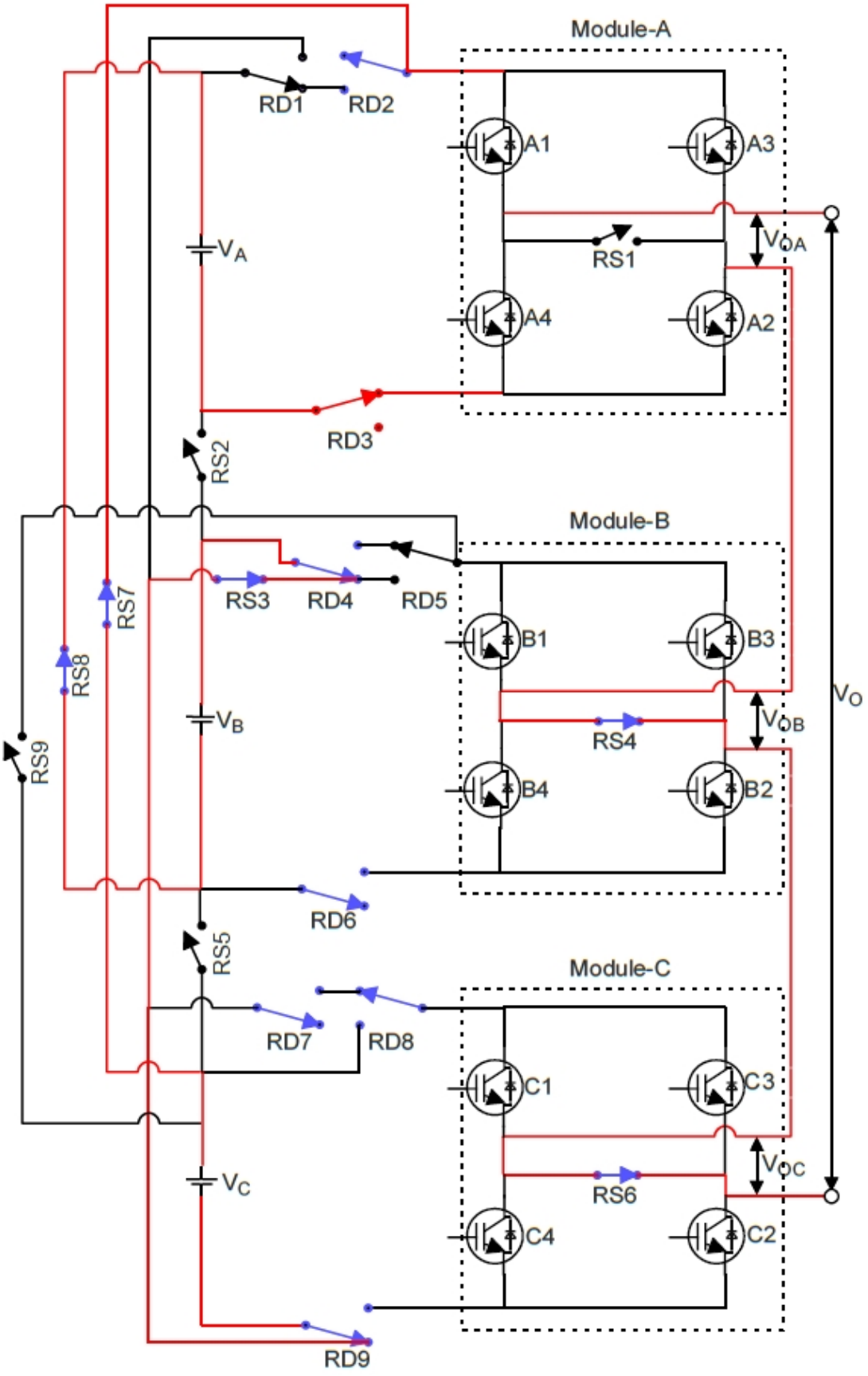

Figure 3.9: Current flow during Mode-5

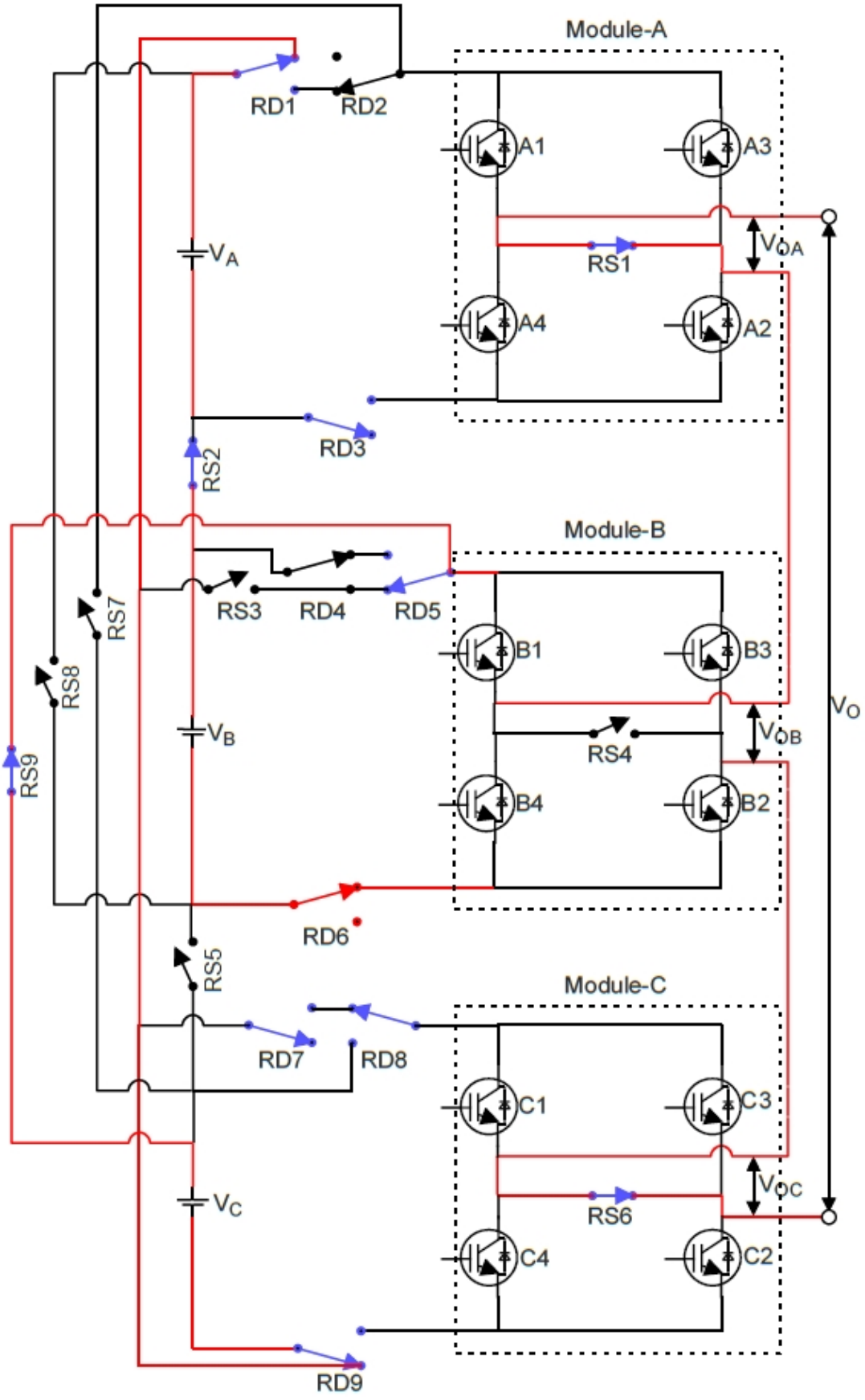

Figure 3.10 Current flow under Mode-6