Independent Control of Two-PMSM Fed by Two SVPWM Inverters with Fault Tolerant Operation

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Abstract-This paper presents an implementation of an independent control of two-mechanically coupled Permanent Magnet Synchronous Motor (PMSM) fed by two Space Vector Pulse Width Modulation (SVPWM) inverters in a separate mode and in the event of failure one leg of one inverter, fault tolerant mode. In a fault tolerant mode, the two motors can operate in an independent control strategy from one inverter with five legs to maintain a constant output coupled torque. The Field Oriented Control (FOC) strategy is used to control the stator current of the two motors through two separate paths. Such application is used in the field of a coupled torque produced by multi-motors such as in subway applications. The whole system is simulated in Matlab /Simulink and the simulated results show a stable and robustness system which can maintain a constant developed torque with a velocity reaches to the rated under fault tolerant operation.

Keywords: PMSM, VSI, SVPWM, FOC, Fault tolerant operation.

I. INTRODUCTION

Permanent magnet synchronous motor is widely used in lower and mid power applications such as computer peripheral equipment, robotics, and is being considered in high power applications such as in, electric vehicles, railway, and industrial drives. The PMSMs have high efficiency, low torque ripple, and superior dynamic performance.

The technique of SVPWM has become the most important technique for three phase voltage Source Inverter (VSI) to control AC induction motors, and PMSMs. In SVPWM technique, the reference voltage is generated by resolving a reference voltage vector. The magnitude and frequency of the output voltage from the VSI are controlled by the magnitude and frequency of the reference voltage vector. The advantages of the SVPWM technique provide efficiently utilization for the DC bus voltage, and generate less harmonic distortion in the output of the three-phase VSI [1].

An adequate speed and dynamic response of PMSM can be realized by vector control with closed loop feedback. This control method can be achieved by field oriented control for the stator current vector. In application that requires several motors drive a common load such as is subway train, either one high power (VSI) feeds the motors in classical system [2,3] or each motor is fed from a separate VSI with independent control circuit [4].

In the event of failure one leg from one VSI, the motor connected to that inverter stop working and may cause to defect the combined output torque and speed. If the load is driven by two motors, the faulted VSI can be isolated and that motor is highly desirable to be driven from the rest VSI in the event of five legs, fault tolerant operation. With the fault tolerant operation, the two motors operate independently in which the faulty and healthy inverters are reconfigured to obtain five legs inverter.

The fault tolerant operation of PMSMs for subway applications is proposed in [4] with three different operation modes, normal, isolation, and fault tolerant modes. A two-PMSM are fed separately from two VSI in normal mode and only one motor is operated in isolation mode when fault is occurred in one VSI, the two motors are operated from the same VSI with five leg VSI in fault tolerant mode. In fault tolerant mode the maximum output torque can be maintained while the speed is decreased to half of the maximum speed.

In this paper, two PMSMs are driven by two-three legs VSI with independent control paths. The maximum output torque and speed can be maintained when a leg of a standard three legs inverter is failed, this leg is isolated and the two motors will operate in a fault tolerant mode from the two VSI in the five leg inverter configuration. The maximum torque can be maintained constant and the speed can be reduced to ratio less than 1 p. u. In this case the legs currents will be around its value due to the proper selection of the common leg in the five leg formulation. The system speed is increased up to 1 p.u. in this paper with an increase in the common leg current up to 2 p.u. The two motors phase to phase voltage will return to its rated value through an adequate time response.

II. TWO PMSM-MOTORDRIVESTRUCTURE

There are several possible two motors drive configuration regarding coupled output torque and electric power sources. In this work the drive structure consists of two identical motors of PMSM type which are controlled independently from a two separate VSI driven by SVPWM technique as shown in Fig. 1.

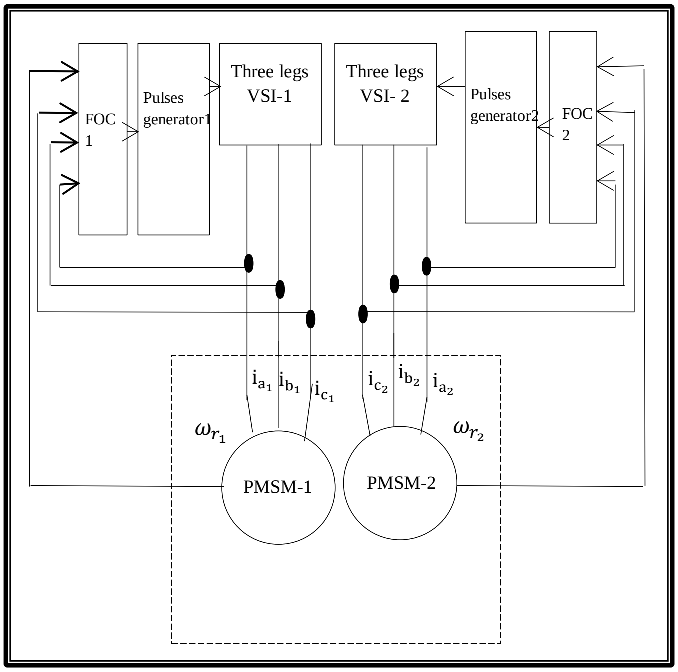

Fig. 1 Independent control of two-PMSMs

When one leg from any of the two inverters fails, the two VSI's will be reconfigured in to five legs inverter as shown in Fig.2. The faulted leg is isolated and common leg will supply two terminals from the two motors and work in overcurrent to produce the same output torque. To overcome the overcurrent in this leg, the nonadjacent selection strategy is used. This strategy can maintain the common leg current to a value around the pre fault condition with 50% speed reduction. When high speed is required, the current in this leg increased up to 2p.u. Therefore all the inverter switches must be designed to handle the required current.

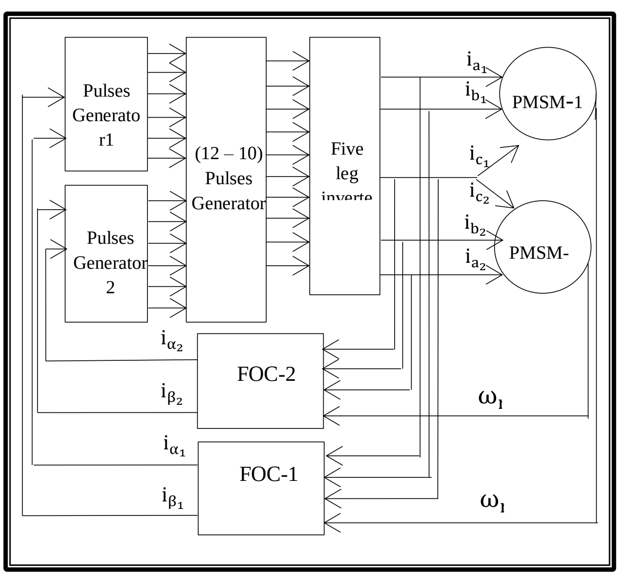

Fig. 2 Five legs inverter strategy

A. PMSM Mathematical Model

The PMSM consist of 3-phase stator windings and rotors with permanent magnets. The stator windings are distributed over pole pairs, with phase axis are spaced by$2\pi/3$ electrical radians.The PMSM mathematical model in rotor reference frame is illustrated in the following equations[5, 6].

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d}\omega_r i_q + \frac{1}{L_d} v_d (1)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q}\omega_r i_d - \frac{1}{L_q}\omega_r \psi_f + \frac{1}{L_q} v_q (2)$$

$$T_{em} = \frac{3}{2}\frac{p}{2}\left(\psi_d i_q - \psi_q i_d\right) \quad (3)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}\left(T_{em} + T_{mech} + T_{damp}\right)(4)$$

WhereR_s is stator resistance,L_d, L_q are the dq rotor inductances,ω_r is rotor angular velocity,ψ_f is the permanent magnet flux,i_d, i_q, v_d, v_q are stator currents and voltages in dq axis,ψ_d, ψ_q are flux linkage when referring to d and q axis,T_{em} is electromagnetic torque,T_{damp} is fractional torque,T_L is load torque; and J is the rotor inertia [5,7].

B. Three Phase VSI Based SVPWM Technique

The three-phase VSI is a DC-AC power converter, the main purpose of the VSI is to provide three phase voltage source to feed the PMSM stator winding, where the amplitude and frequency of the voltages are always be controllable. The control technique used for controlling the inverter output voltage and frequency is the space vector pulse width modulation (SVPWM). It is based on the voltages in the stationary $\alpha\beta$reference frame, which are obtained by transforming the three phase voltages by Clarke transformation. The magnitude of the reference voltage vector can be found from the voltages in the stationary $\alpha\beta$ reference frame and used for modulating the VSI output. The result is six non-zero vector (V_1 toV_6) and two zero vector ($V_0$and V_7) that shaped a hexagon as shown in Fig.3.Theeight switching states of the inverter legs are shown in Table I [8].

TABLE I
The Switching Table and the Output Voltage of the VSI

Voltage vectors	Switching Vectors			phase voltages			Line voltages		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
v_0	0	0	0	0	0	0	0	0	0
v_1	1	0	0	$2/3$	$-1/3$	$-1/3$	1	0	-1
v_2	1	1	0	$1/3$	$1/3$	$-2/3$	0	1	-1
v_3	0	1	0	$-1/3$	$2/3$	$-1/3$	-1	1	0
v_4	0	1	1	$-2/3$	$1/3$	$1/3$	-1	0	1
v_5	0	0	1	$-1/3$	$1/3$	$2/3$	0	-1	1
v_6	1	0	1	$1/3$	$-2/3$	$1/3$	1	-1	0
v_7	1	1	1	0	0	0	0	0	0

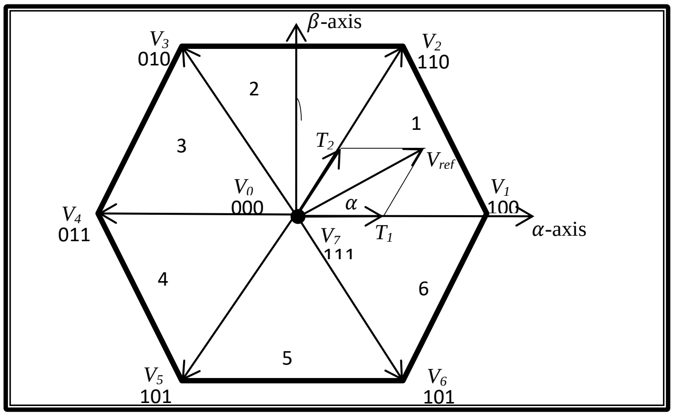

Fig. 3 Switching vectors and voltage sectors

C. Field Oriented Control (FOC)

Field oriented control method (FOC) controls the stator current vector by transferring the three-phase currents and speed of the motor to obtain a required v_d and v_q voltages. The three-phase stator currents are transferred in to two phase $\alpha\beta$ system and then transfer to two phase dq system. The speed of the rotor is detected using speed sensor and compared with the synchronous reference speed and then controlled through PI controller to produce the reference i_q current, which used to control the torque of the motor. The quadrature axis current i_q of the motor compared with the reference i_q and by using another controller to produce the required quadrature voltage v_q of the voltage vector of the SVPWM inverter. The direct axis current i_d of the motor is compared with zero and by using other controller to produce the desired direct axis voltage v_d of the voltage vector. The maximum torque control is achieved by controlling i_q and i_d=0, as shown in Fig. 4 [9].

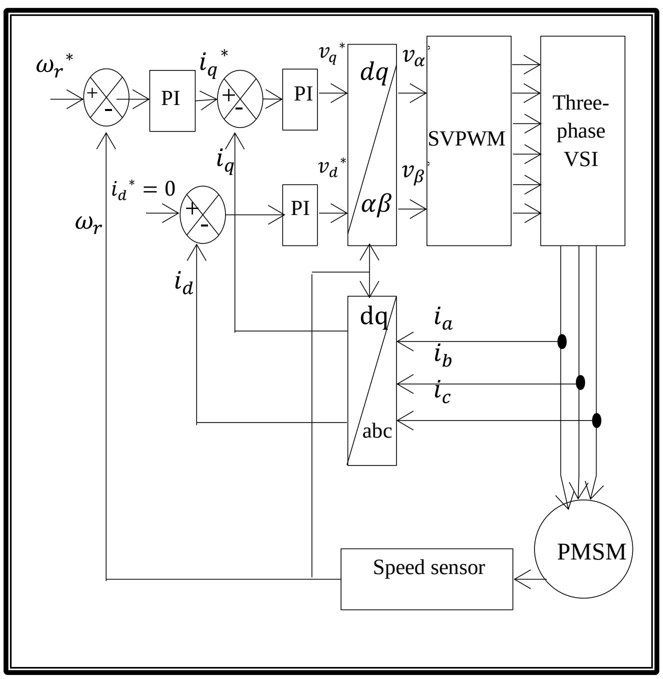

Fig. 4 FOC strategy

III.NORMALTOFAULTTOLERANTOPERATINGPROPOSEDSTRATGY

At normal operation, two three-phase PMSMs are controlled using two three-phase VSI. When one leg in one of the VSI fails, the associated PMSM fails to operate, and if the two PMSMs are used for traction application then it significantly affects the traction force especially at heavy load (like in subway application). This problem can be avoided by applying fault tolerant mode, in which the two VSI are reconfigured to one five legs inverter.

A. Configuration of Five-Leg Inverter

The five legs two motor drive structure contains ten switches (S1 to S10) instead of twelve switches in the standard dual three-phase VSI. Fig.5 shows five legs inverter supplies two three-phase PMSMs. Phase a_1, and b_1 of the PMSM-1 are connected to the inverter legs A and B respectively. Phase a_2, and b_2 of the PMSM-2 are connected to the inverter legs F and E respectively. Inverter leg C is connected to c_1, and c_2 of both motors.[6]

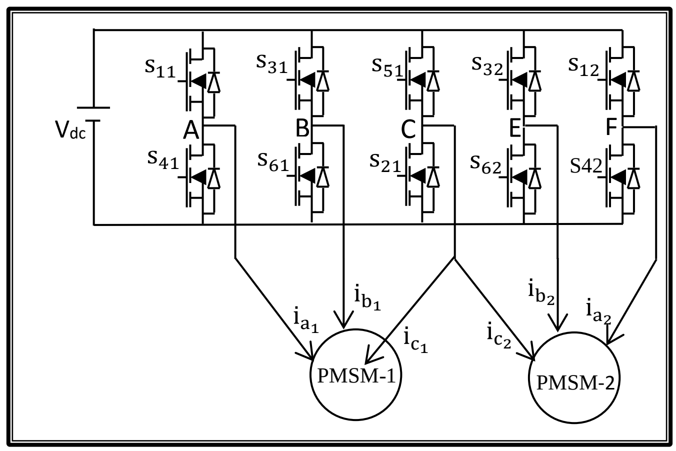

Fig. 5 Five legs inverter supplies two motors drive

B. Control Method of the VSI in Normal and Fault Tolerant Operation

The control method includes two levels: machine level control and system level control. The machine level control method is the typical control method for the PMSM controlled using vector control with VSI modulated by SVPWM. The machine level control method is used in the normal mode. The machine level control method and system level control method are used in the fault tolerant mode. In the fault tolerant mode the faulty inverter and the healthy inverter are reconfigured to obtain five legs inverter. For example, if leg D is failure, the leg D is locked, and the two three phase VSI reconfigured to be a five leg inverter by setting the Fault Tolerant Bridge (FTB) according to Table II. Fig. 6 shows the FTB. The control in the fault tolerant mode utilized the duty cycles of two three phase VSI to generate the modulation signals for all legs of the five legs inverter[4].

TABLEII.
FTB Configuration Topology

No of fault leg	Reconfiguration topology	Switching signals for the FTB
A	AF	011111000000000000000100
	AE	011111000000000000100000
	AD	011111000000000100000000
B	BF	101111000000000000000010
	BE	101111000000000000010000
	BD	101111000000000010000000
C	CF	110111000000000000000001
	CE	110111000000000000001000
	CD	110111000000000001000000
D	DA	111011001000000000000000
	DB	111011000001000000000000
	DC	111011000000001000000000
E	EA	111101010000000000000000
	EB	111101000010000000000000
	EC	111101000000010000000000
F	FA	111110100000000000000000
	FB	111110000100000000000000
	FC	111110000000100000000000

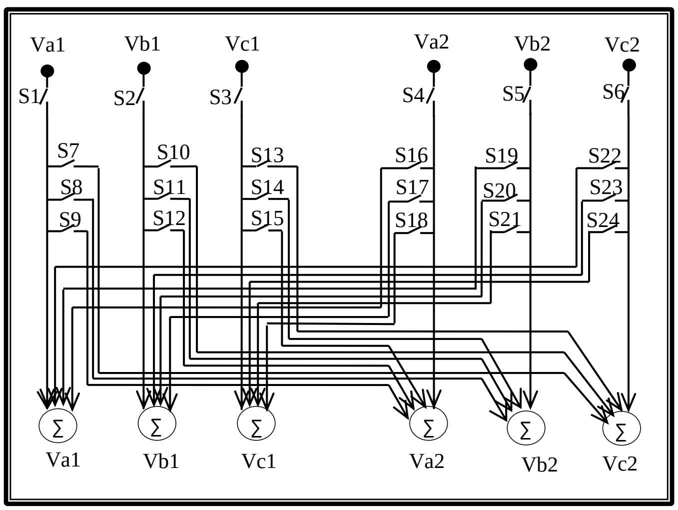

Fig. 6 The fault tolerant bridge

In the fault tolerant mode, the faulty leg is isolated and an another leg is a led to feed the motor terminal as shown in Fig.5, and that may increase the current in the common leg to the summation of the two connected phase currents. The nonadjacent selection principle is used to find the optimal leg from the three legs of the healthy VSI to be connected in the common leg to protect it from the overcurrent. To satisfy the nonadjacent selection principle the phase difference between the two connected phase currents must be satisfy (5).

$$\frac{2\pi}{3} \leq \Delta\theta \leq \frac{4\pi}{3} \qquad (5)$$

Where: $\Delta\theta = \theta_2 - \theta_1$,$\theta_1$ and θ_2 are the phase angles of the two connected phase of PMSM-1and PMSM-2 respectively.

The common leg is selected according to Table.III to ensure that the phase difference is according to (5) [4].

TABLE III
Common Leg Selection Table

Phase difference between two PMSMs	Faulted leg	Reconfiguration topology
$0 \leq \Delta\theta \leq \frac{2\pi}{3}$	A	AE
	B	BD
	C	CF
	D	DB
	E	EA
	F	FC
$\frac{2\pi}{3} \leq \Delta\theta \leq \frac{4\pi}{3}$	A	AF
	B	BE
	C	CD
	D	DC
	E	EB
	F	FA
$\frac{4\pi}{3} \leq \Delta\theta \leq 2\pi$	A	AD
	B	BF
	C	CE
	D	DA
	E	EC
	F	FB

At any time, when an upper switch is switched on the corresponding switch is switched off. Therefore, the states of upper switches s_{11}, s_{31}, s_{51}, s_{32}, and s_{12} can be used to determine the output voltage. The duty cycle (δ) for any phase of the inverter is equal to the (ON) time of the phase over the switching period (*Tz*). From the machine level control method the three-phase duty cycles of the PMSM-1 can be obtained and named as (δ_{a_1}, δ_{b_1}, δ_{c_1}) for phase (a_1, b_1, c_1) respectively. Similarly the three-phase duty cycle of the PMSM-2can be obtained and named as (δ_{a_2}, δ_{b_2}, δ_{c_2}) for phase (a_2, b_2, c_2) respectively.[9]

When leg c_2 of one standard dual inverter is failure, the faulty leg is isolated by a specific switch and the two three phase VSI reconfigured to be a five leg inverter , in which phase a_1, phase b_1, phase a_2, and phase b_2 connect to leg-A, leg-B, leg-F, and leg-E, respectively. Phase c_1 and phase c_1 share leg-C. The difference between the duty cycle of phase and the duty cycle of the common leg is called the common-leg-based modulation ratio. Since the common leg is (leg-C), the common-leg-based modulation ratio for the VSI-1 and VSI-2 are [4]:

$$m_{AC} = \delta_{a_1} - \delta_{c_1} (6) \quad m_{BC} = \delta_{b_1} - \delta_{c_1} (7) \quad m_{CC} = 0 (8) \quad m_{EC} = \delta_{b_2} - \delta_{c_2} (9) \quad m_{FC} = \delta_{a_2} - \delta_{c_2} (10)$$

Where; m_{AC},m_{BC},m_{CC},m_{FC},m_{EC} are the common-led-based modulation ratio [4].

The duty cycles of the legs (δ_{a_1}, δ_{b_1}, δ_{c_1}, δ_{a_2}, δ_{b_2}, δ_{c_2})can be obtained from the machine level control method and determine the common-leg-based modulation ratios. The value of any leg duty cycle is in the range [0, 1].

The maximum and minimum values of the common-leg-based modulation ratios are:

$$m_{max-C} = \max\{m_{AC}, m_{BC}, m_{CC}, m_{FC}, m_{EC}\} \qquad (11)$$

$$m_{min-C} = \min\{m_{AC}, m_{BC}, m_{CC}, m_{FC}, m_{EC}\} \qquad (12)$$

when a fault occur in one leg of the voltage source inverter (VSI) the fault tolerant mode is applied, in which the faulty inverter and the healthy inverter are reconfigured to obtain five legs inverter. To obtain the five legs inverter new values of the duty cycles ($\delta_{a_1}, \delta_{b_1}, \delta_{c_1}, \delta_{a_2}, \delta_{b_2}$)must be determined according to the configuration of the five legs inverter. Since the values of the common-leg-based modulation ratios (m_{AC},m_{BC},m_{CC},m_{FC},m_{EC}) have no change in the five legs inverter configuration, according to(6-10) all new values of the duty cycles can be determined if the new value of δ_{c_1} is obtained. To avoid the occurrence of the over modulation δ_{c_1} must be determined as follow: [9]

$$\delta_{c_1} = 0.5(\delta_{max-c} + \delta_{min-c})(13)$$

Where:

$$\delta_{max-c} = \min\{1,1 - m_{max-c}\}(14)$$

$$\delta_{min-c} = \max\{0, -m_{min-c}\}(15)$$

C. The Proposed Method for Detection of the Faulted Leg

The fault tolerant mode is selected when one leg of VSI is faulted. The leg is in fault when any one of its switches is open, short circuit, or not receive the gate signal. When fault happens in leg, the fault is detected using a proposed method, in which a voltage across each switch is measured continuously. It must be zero and reverse voltage depending on the switching frequency, if the reverse voltage on the switch not repeated during three times of the switching frequency the leg is regard a faulted leg, and then the fault tolerant mode is selected through selection switch as shown in Fig.7.

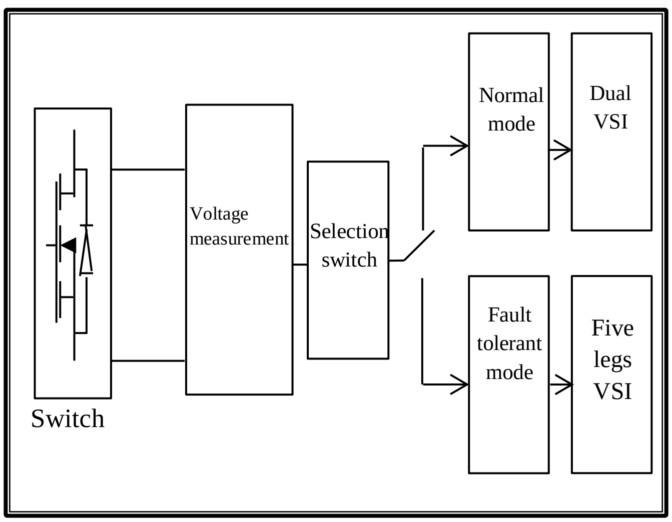

Fig. 7 Suggestion method of fault detection

IV. IMPLEMENTED SIMULINK MODEL

The Simulink model of the proposed control is implemented of two100 kW, 400 V, 4 pole, 60 Hz three-phase PMSM that can be operated from dual VSI and auto converted to operate from five-leg inverter with applying FOC for each motor.

Two duty cycles generators are implemented using the SVPWM technique, which is based on the voltages in the stationary $\alpha\beta$reference frame. In the duty cycles generator the duty cycle of operation for the three legs of the VSI are determined. A matlab function is using to determine the duty cycles of the three legs according to the reference voltage vector V_{ref} and time durations T_1, T_2, T_0 that determined according to (18-20). after each 60° of one cycle (360°) one inverters leg is change its state and remains constant for 60° interval. Thus for each cycle (360°) there are six discrete values of leg voltages. Fig.8 shows the Simulink model of the duty cycles generator.

$$|V_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2}(16)$$

$$\alpha = tan^{-1}\left(\frac{V_\alpha}{V_\beta}\right) = 2\pi f t(17)$$

Where; (f) is the fundamental frequency.

$$T_1 = \frac{\sqrt{3}T_z|V_{ref}|}{V_{dc}} sin\left(\frac{n}{3}\pi - \alpha\right)(18)$$

$$T_2 = \frac{\sqrt{3}T_z|V_{ref}|}{V_{dc}} sin\left(\alpha - \frac{n-1}{3}\pi\right)(19)$$

$$T_0 = T_z - (T_1 + T_2)(20)$$

Where: (n) Is the number of sectors (from 1 to 6), $0 \le \alpha \le 60°$, and $T_z = 1/f_z$

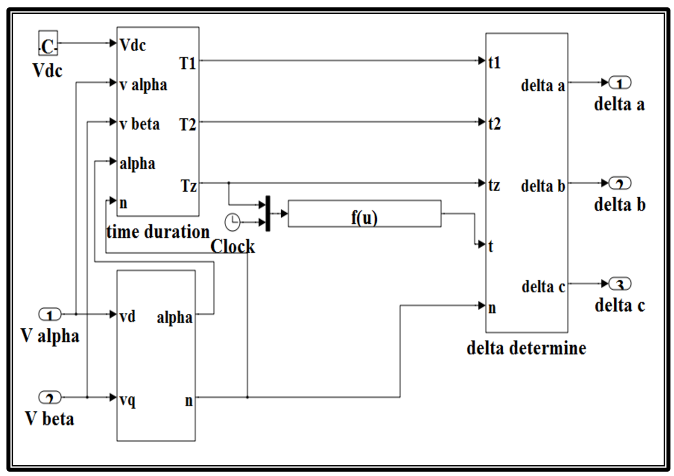

Fig. 8 Simulink model of the duty cycles generator

Two types of pulses generator are implemented the first one generate switching signals to the dual VSI at normal mode operation with no fault occur and the second one generate switching signals to the five legs VSI at fault tolerant mode operation when fault occur in one leg of one VSI. matlab function are used in the pulses generator to generate switching signals depending on the determined duty cycles.Fig.9 shows the Simulink model of the pulses generator.

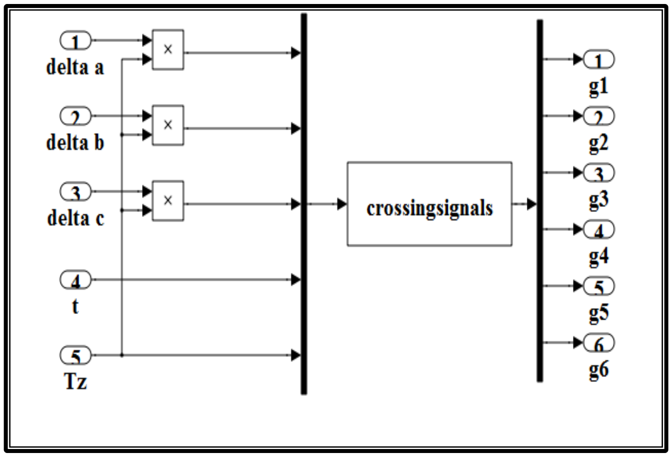

Fig. 9 Simulink model of the pulses generator

Selector switches are used to select the switching signals from which pulses generator (normal mode pulses generator or fault tolerant mode pulses generator) that used to fed the VSI. Dual three-phase VSI is implemented using MOSFET switches and one common DC bus voltage. At time 3 sec of operation leg c_2 is fault and isolated from the dual VSI, the fault tolerant operation is applied and the dual three-phase VSI operate as five-leg inverter.

The FTB is implemented using 24 switches, which select the proper dual three-phase VSI legs that connect to the two PMSMs terminals. Three-dimension direct lookup table is implemented to operate the FTB according to TableIII, which specify the common leg according to the phase difference between the two PMSMs and faulted leg. Fig. 10 shows the Simulink model of the FTB.

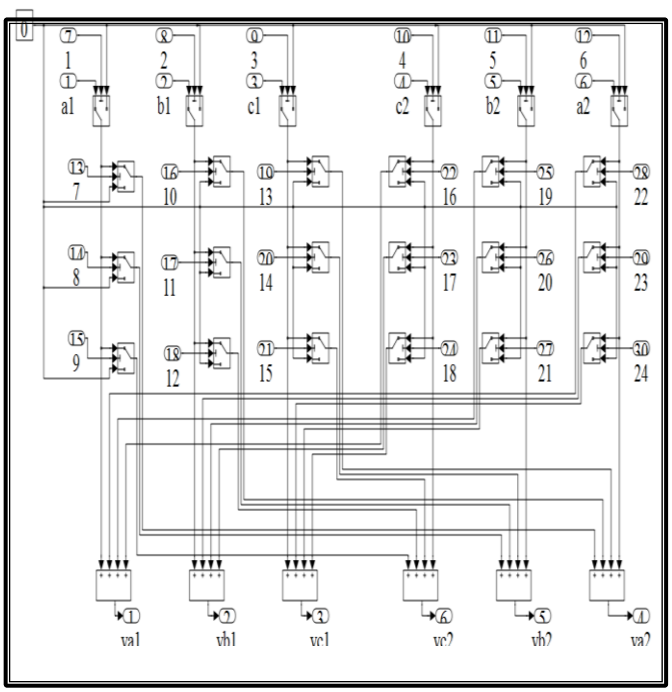

Fig. 10 Simulink model of the FTB

Two Simulink model of the PMSM are implemented. Using Clarke transformation to transfer the input three-phase voltage to the αβ reference frame and Park transformation to transfer voltages in αβ reference frame to thedq reference frame. The rotor speed of the motor, the torque, and motor current in the dq reference frameare determined according to (1-4). Using inverse Park and Clark transformations to transfer the motor currents in the dq reference frame to the abc reference frame. The two PMSMs are fed from the FTB and controlled using FOC technique. Fig. 11 shows the Simulink model of the PMSM.

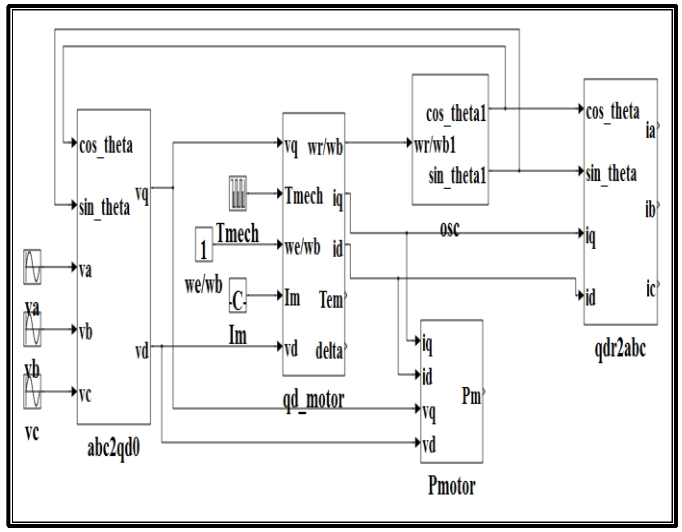

Fig. 11 Simulink model of the PMSM

The FOC method is implemented using Clarke and Parke transformation to transfer the motor currents from the abc reference frame to dq reference frame, and then using three PI controllers to obtain the proper voltage in dq reference frame, which converted to the αβ reference frame using inverse Park transformation. Fig. 12 shows the Simulink model of the FOC method.

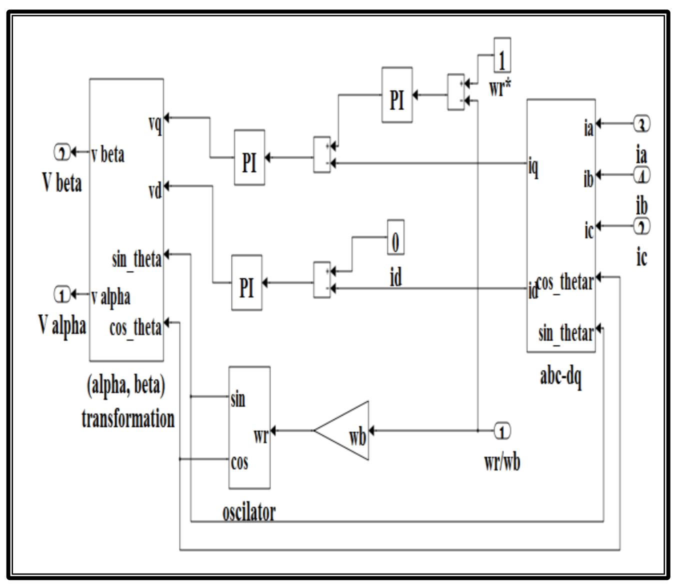

Fig. 12 Simulink model of FOC method

The Simulink model of fault tolerant operation strategy is shown in Fig. 13.

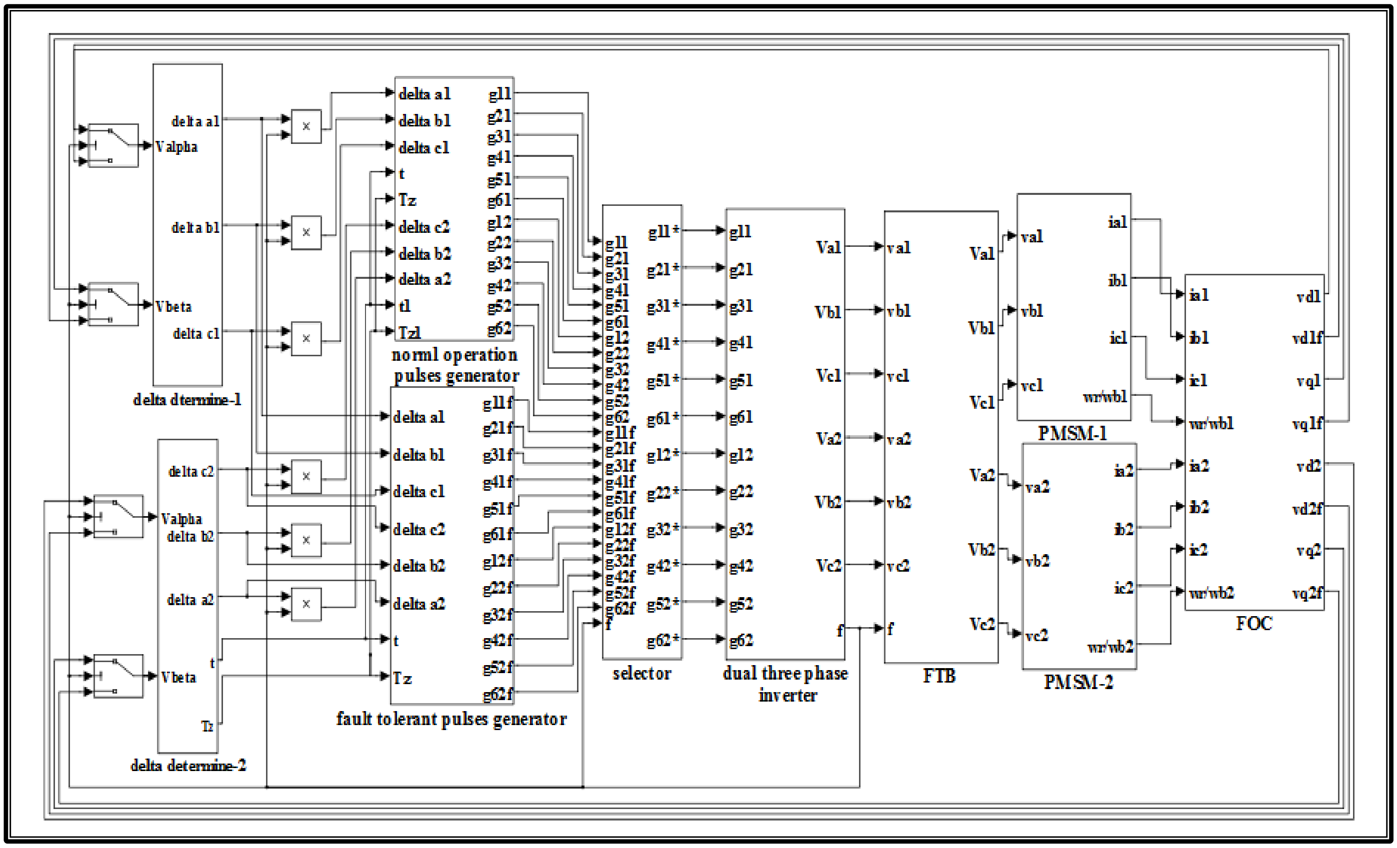

Fig. 13 Simulink model of the field tolerant strategy

V. SIMULATION RESULTS

The simulation results are determined for motors operate to load as shown in Fig. 14. At time 3 sec. of operation fault occur at legc_2 of the second VSI and fault tolerant mode operation automatically applied, in which the two VSI are reconfigured to one five leg inverter and the leg c_1 is become a common leg connected to terminal c_1 and c_2 of PMSM-1and PMSM-2 respectively. At time 5 sec. the fault is clear and return to the normal mode operation. Simulation results of different reference speed are implemented. The simulation results of reference speed 0.5 p. u. are shown in Fig. 15. The simulation results of reference speed 0.7 p. u. are shown in Fig. 16. The simulation results of reference speed 1 p. u. are shown in Fig. 17.

As shown in Fig. 15, the motors at first operates in the normal mode and maintain to maximum speed and maximum torque with currents not increase 1 p. u. until the fault occur at time 3 sec. the fault tolerant mode is applied and the reference speed of the motors is decreased to 0.5 p. u. while the motors can operate at full load torque without increase the rms values of the motors currents. When the fault is cleared at time 5 sec. the normal mode is applied again and the speed of the motors return to the maximum speed.

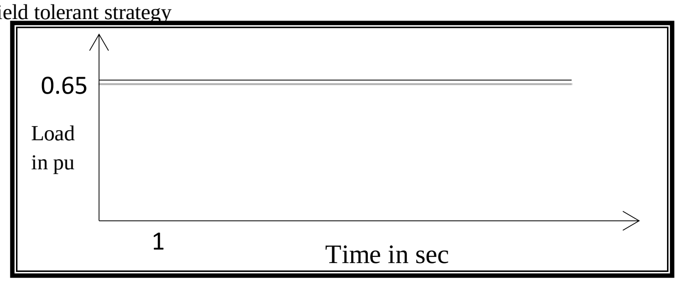

Fig. 14 Step load change applied to motors

Fig. 16 shows the simulation results when reference speed for the fault tolerant mode operation is increased to 0.7 p. u., the PMSMs supply the full load torque in the normal mode and the fault tolerant mode and the motors rms current not increase 1 p. u., The overshot in the speed is smaller than that at reference speed 0.5 p. u. and the common leg rms current not increase more 1 p. u.

Fig. 17 shows the simulation results when reference speed for the fault tolerant mode operation is increased to 1 p. u., the PMSMs supply the full load torque in the normal mode and the fault tolerant mode and the motors rms current not increase 1 p. u., The overshot in the speed is smaller than that at reference speed 0.7 p. u. and the common leg rms current is greater than 1 p. u.

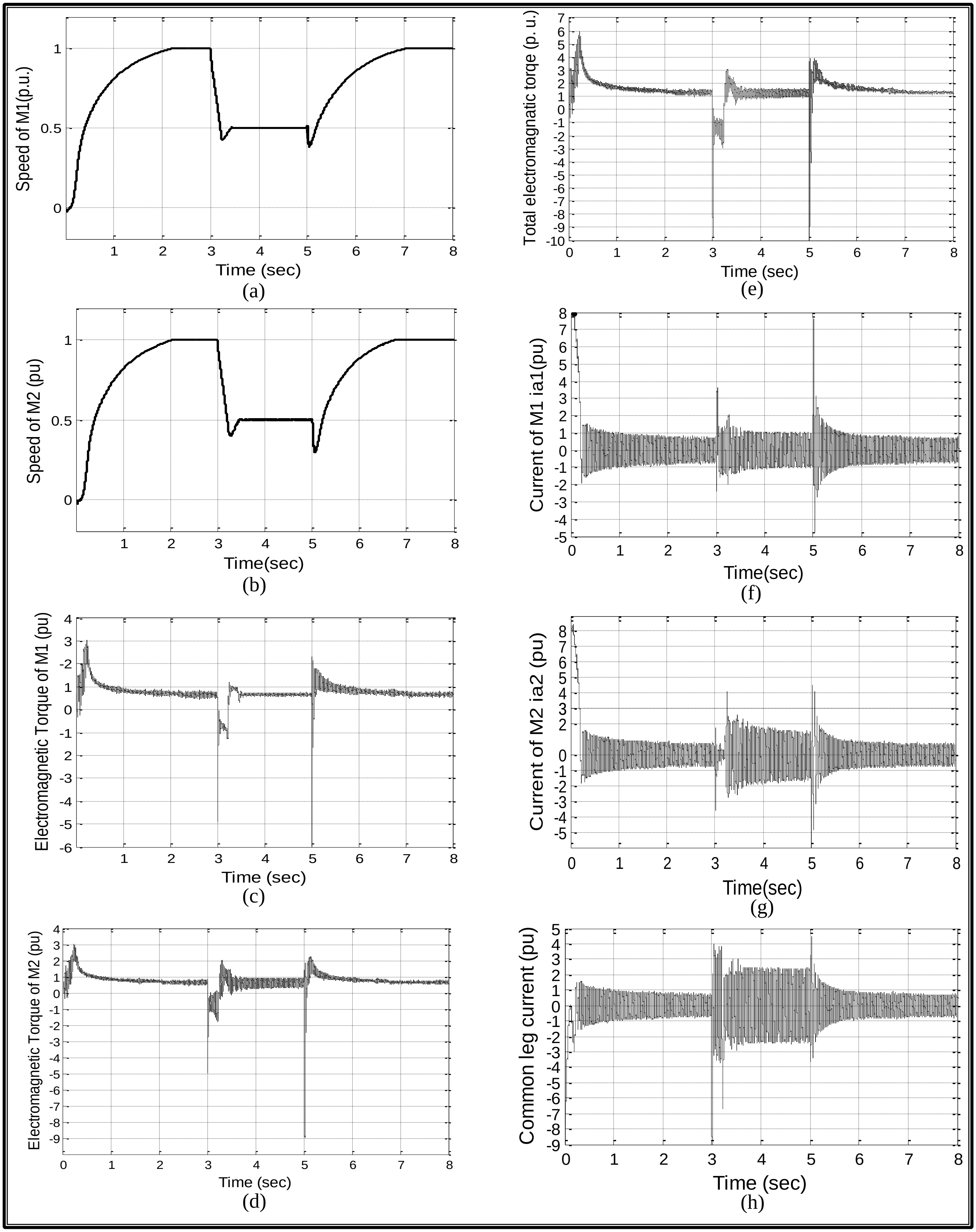

Fig.15 Simulation result at reference speed 0.7 p. u. for normal and fault tolerant mode. (a) speed of PMSM-1, (b) speed of PMSM-2, (c) electromagnetic torque of PMSM-1, (d) electromagnetic torque of PMSM-2, (e) total electromagnetic torque, (f) current of PMSM-1, (g) current of PMSM-2, (h) common leg current

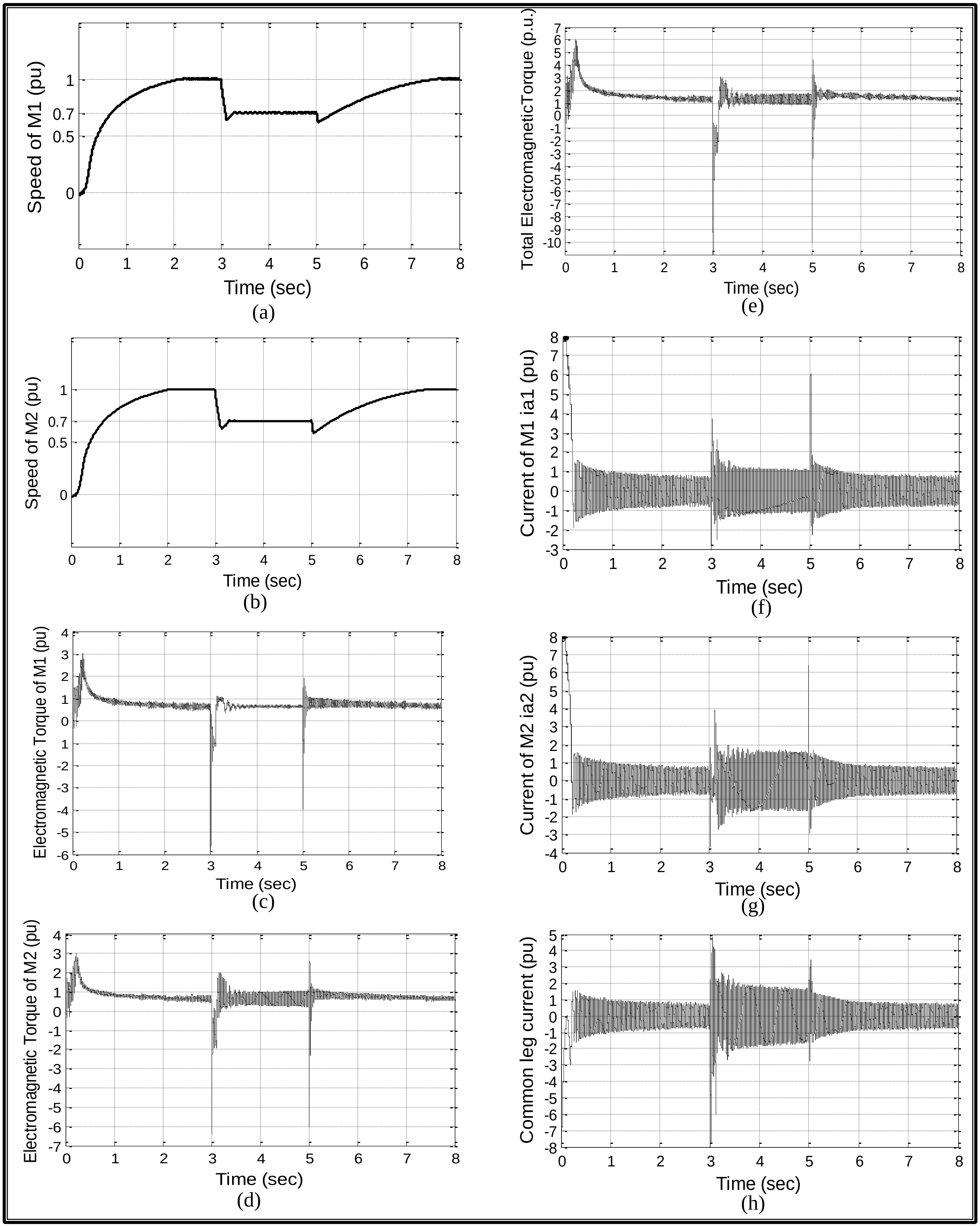

Fig.16 Simulation result at reference speed 0.7 p. u. for normal and fault tolerant mode. (a) speed of PMSM-1, (b) speed of PMSM-2, (c) electromagnetic torque of PMSM-1, (d) electromagnetic torque of PMSM-2, (e) total electromagnetic torque, (f) current of PMSM-1, (g) current of PMSM-2, (h) common leg current

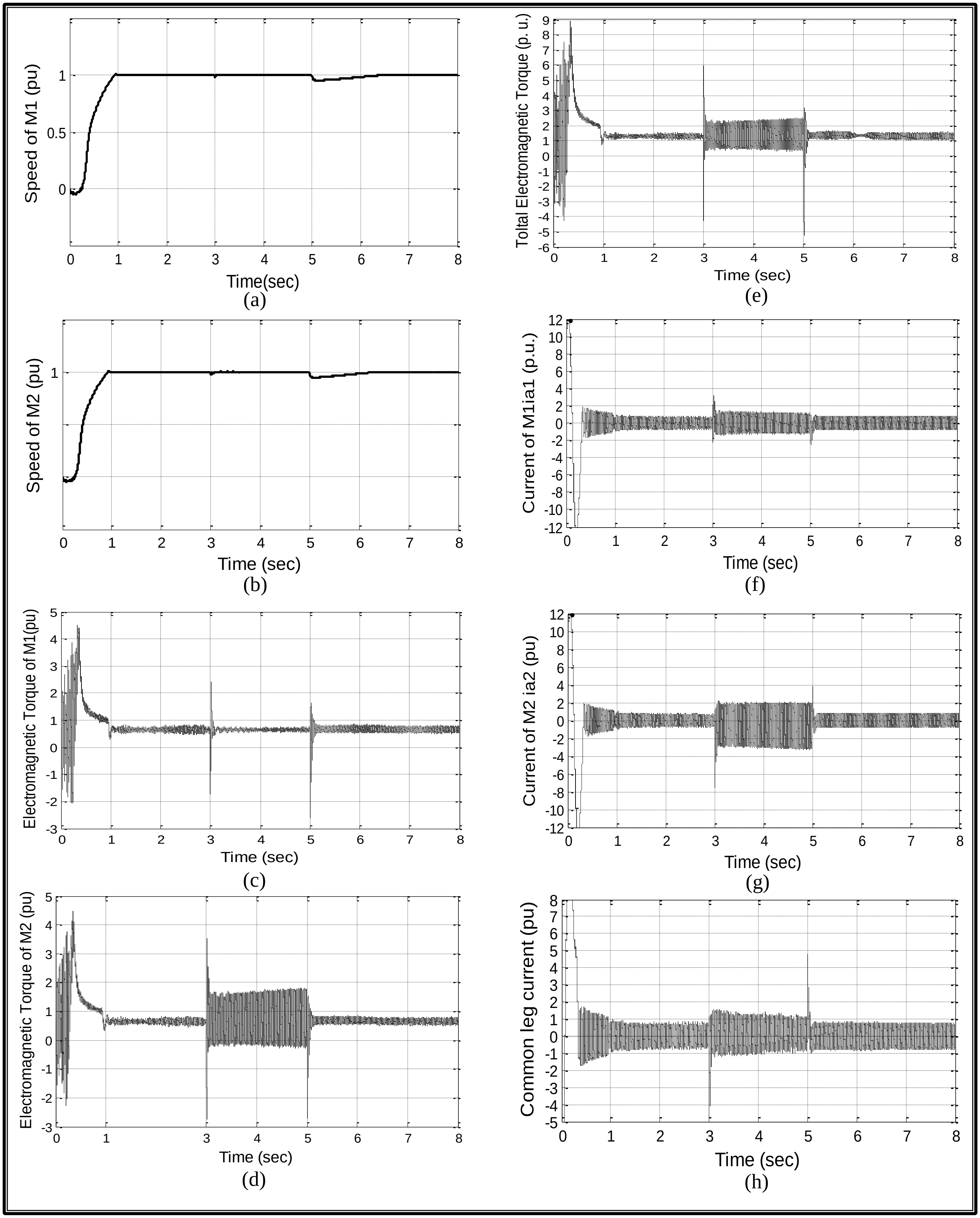

Fig.17 Simulation result at reference speed 0.7 p. u. for normal and fault tolerant mode. (a) speed of PMSM-1, (b) speed of PMSM-2, (c) electromagnetic torque of PMSM-1, (d) electromagnetic torque of PMSM-2, (e) total electromagnetic torque, (f) current of PMSM-1, (g) current of PMSM-2, (h) common leg current

VI. CONCLUSION

In this paper two PMSMs are controlled independently using dual three-phase VSI at normal operation , In the event of failure one inverter leg the both PMSMs auto converted to operate according to the fault tolerant mode operation, in which the faulty inverter and the healthy inverter are reconfigured to obtain five legs inverter. Pulse width modulation method is used to operate the VSIs. The Simulink model of the PMSMs with independent control in normal and fault tolerant operation is implemented, two pulse generators of the standard three-phase inverter are used, and two vector control for both motors are implemented using PI controller. The simulated results show a stable and robustness system which can maintain a constant developed torque with a velocity reaches to the rated under fault tolerant operation.

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