International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-9 Issue-1, May 2020

Modeling of Three Phase Induction Motor with Dtc Drive Fault Analysis using Fuzzy Logic

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Abstract: ***Three phase induction motor drives are the most widely used drives in heavy load industries Because of its wide usage in industry, a small fault occurring in the motor drive may cause huge damage and results in failure of heavy machinaries.Inorder to avoid these failures, all the possible faults that may occur in induction motors are analysed. Based on the analysis performed, the parameters that may cause faults in the drive system are monitored. Even a minute change in the parameters are monitored using an intelligent control method named Fuzzy based monitoring system. In this monitoring system, induction motor drive is adopted with a direct torque control method to avoid the usual torque ripples present in the system. Thisintelligent fault monitoring system is used to take corrective measures within a specified time when the drive is implemented in an electric vehicle applications.***

Keywords : Induction motor, Faults, DTC drive, Space Vector PWM, Hysteresis controller, Fuzzy monitoring system.

I. INTRODUCTION

Most widely used AC motors in drives and control of domestic and industrial purpose are single phase and three phase induction motors. They have more advantages over other ac and dc motors. It is reliable in nature and also it is more economical than any other drive system. Also, these motors can be operated for both the application drives, related to frequency such as fixed and variable. Different types of fault that occurs in the drive, mainly alters one particular parameter of the motor which is monitored for feasible detection and diagnosis. The parameter monitored is the current through the three phase stationary part (stator) of an induction motor with respect to time till the sudden change in current exists. The system chosen for monitoring the parameters must be sensitive to minor deviations. Even though the monitoring system is high competent in detection of fault, diagnosis of such faults should be performed at right time or else the machine fails. In order to overcome these issues and perform the desired objectives, fuzzy logic based intelligent monitoring system is developed[1].

The major control is achieved by estimating the flux and torque value[2]. The current in stationary part at standstill reference frame can be chosen for DTC drive. The current in stationary part at rotating reference frame can be chosen for field orientation control drive[3]. The healthy nature of induction motor is decided with the help of linguistic variables framed for the parameters monitored in MATLAB Simulink fuzzy controller[4][5]. In this paper, all possible faults are monitored using online fuzzy monitoring system.

II. INDUCTION MOTOR IN DQ AXIS

Squirrel cage Induction machine with dynamic performance is modeled using D-Q axis at standstill reference frame[6]. The equivalent circuit for the D-Q reference axis is shown below:

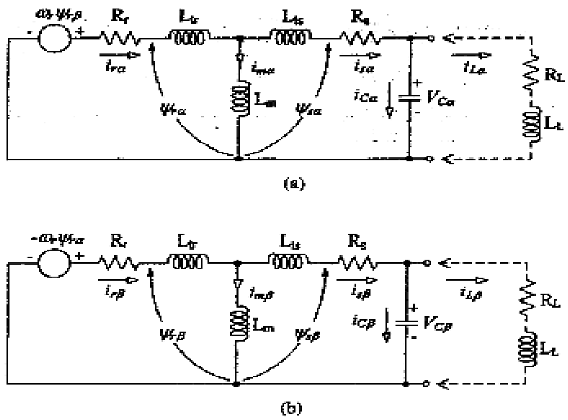

Fig. 1. Equivalent Circuit.

The parameters of stationary and rotational parts are derived from the equivalent circuit for D-Q axis as follows:

$$V_{sd} = R_s i_{sd} + L_s \frac{d}{dt} i_{sd} + L_m \frac{d}{dt} i_{rd} \quad (1)$$

$$V_{sq} = R_s i_{sq} + L_s \frac{d}{dt} i_{sq} + L_m \frac{d}{dt} i_{rq} \quad (2)$$

$$0 = R_r i_{rd} + L_r \frac{d}{dt} i_{rd} + L_m \frac{d}{dt} i_{sd} + \omega_r \Psi_{rq} \quad (3)$$

$$0 = R_r i_{rq} + L_r \frac{d}{dt} i_{rq} + L_m \frac{d}{dt} i_{sq} - \omega_r \Psi_{rq} \quad (4)$$

Flux linkage parameters of stationary and rotational part are derived from the equivalent circuit for D-Q axis as follows:

$$\Psi_{rd} = L_m i_{sd} + L_r i_{rd} + \Psi_{rd0} \quad (5)$$

$$\Psi_{rq} = L_m i_{sq} + L_r i_{rq} + \Psi_{rq0} \quad (6)$$

Manuscript received on April 01, 2020.
Revised Manuscript received on April 25, 2020.
Manuscript published on May 30, 2020.

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Where Ψ_{rd0} and Ψ_{rq0} are residual flux linkage parameters of stationary and rotational part.

The rotational speed of the electrical rotor in induction machine is ω_r with respect to voltage in rotational part at standstill reference frame are as follows:

$$\omega_r\Psi_{rd} = \omega_r L_m i_{sd} + \omega_r L_r i_{sd} + \omega_r\Psi_{rd0} \qquad (7)$$

$$\omega_r\Psi_{rq} = \omega_r L_m i_{sq} + \omega_r L_r i_{sq} + \omega_r\Psi_{rq0} \qquad (8)$$

The change in voltage parameter of the capacitor in the equivalent circuit is expressed as follows:

$$V_{cd} = \frac{1}{c}\int i_{cd}\, dt + V_{cd0} \qquad (9)$$

$$V_{cq} = \frac{1}{c}\int i_{cq}\, dt + V_{cq0} \qquad (10)$$

From the equivalent circuit of the induction machine, the vector equation in D-Q reference frame of machine in no load at standstill frame are given by

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix} = \begin{bmatrix} R_s+pL_s & 0 & pL_m & 0 \\ 0 & R_s+pL_s & 0 & pL_m \\ & pL_m\omega_r L_m R_r + pL_r & \omega_r L_r & \\ -\omega_r L_m pL_m & & -\omega_r L_r & R_r+pL_r \end{bmatrix}\begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix} + \begin{bmatrix} V_{cd}\\ V_{cq}\\ \omega_r\Psi_{rq0}\\ -\omega_r\Psi_{rd0}\end{bmatrix} \qquad (11)$$

From equation 11; the state vector is defined as

$$A_p I_G + BI_G + V_G = 0 \qquad (12)$$

Where,

$$A=\begin{bmatrix} L_s & 0 & L_m & 0\\ 0 & L_s & 0 & L_m\\ L_m & 0 & L_r & 0\\ 0 & L_m & 0 & L_r\end{bmatrix},\ B=\begin{bmatrix} R_s & 0 & 0 & 0\\ 0 & R_s & 0 & 0\\ 0 & \omega_r L_m R_r & \omega_r L_r & \\ -\omega_r L_m & 0 & -\omega_r L_r R_s & \end{bmatrix}$$

$$I_G = \begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix},\ V_G = \begin{bmatrix} V_{cd}\\ V_{cq}\\ \omega_r\Psi_{rq0}\\ -\omega_r\Psi_{rd0}\end{bmatrix}$$

From the above state equation for the parameters derived the DTC technique is applied to control the input of the intelligent monitoring system.

III. SVPWM DTC METHOD FOR INDUCTION MACHINE

The flux and torque of the machine which has direct influence on the current of stationary part is controlled by means of hysteresis scheme with two comparators. By selecting the appropriate supply system with inverter either voltage as source or current as source, the feasible drive system is made[8]. Inverter with voltage as source is designed in this system because of its efficient performance. Here the source voltage is sectioned as 8 different vector planes of operation from which the switching of voltage is performed. The methodology behind SVPWM DTC is to compare the estimated value of control parameters with the predefined data.

A. DTC Method for Control Parameter Estimation

In normal DTC method, control parameters are optimized by 2 comparators of hysteresis type. First control parameter is flux linkage in stationary part and the other parameter is electromagnetic torque. The comparator compares and generates two possible results H_{fe} (0 & 1) for first parameter and three possible results H_{te}(-1, 0&1) for second parameter.

$$F_d = \int(V_d - R_s I_d)dt \qquad (13)$$

$$F_q = \int(V_q - R_s I_q)dt \qquad (14)$$

$$F = \sqrt{(F_d^2 + F_q^2)}\angle \tan^{-1}\left(\frac{F_q}{F_d}\right) \qquad (15)$$

$$H_{te} = \frac{3}{2}P\left(F_{ds}F_{qs} - F_{qs}F_{ds}\right) \qquad (16)$$

This H_{fe} and H_{te} are the inputs to the controller of hysteresis type and the outputs are the voltages switched from each vector planes.

B. Direct Control of Flux Parameter

The state of flux in standstill reference frame is obtained in the vector state as:

$$\overline{\Psi_s} = \int(\overline{V_s} - \overline{I_s}R_s)dt \qquad (17)$$

When the supply voltage to the machine is zero, then the voltage drop across the resistance of stationary part is negligible for control ease.

$$\Delta\overline{\Psi_s} = \overline{V_s}\Delta t\ ) \qquad (18)$$

This shows that the supply voltage applied to the stationary part ($\overline{V}$ s) for an increasing time period Δt, causes the flux parameter ($\overline{\Psi}$s) to alter in an increasing manner. The estimation of flux vector in stationary part is performed using a circle of rotation in which the voltage is placed in a six vector planes. In order to increase or decrease the stationary parts flux, switching of vector plane of suitable voltage is done. The command from the comparator of flux vector turns on in counter clockwise motion in a circle whereas the real flux vector in stationary part ($\overline{\Psi}$s) used to record the trajectory of change in flux in a zigzag manner which is limited inside the hysteresis range.

C. Direct Control of Torque Parameter

Interaction of fluxes in stationary and rotational parts of the machine results in the generation of electromagnetic flux is obtained with the following condition:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_s^{'}L_r}\overline{\Psi_s} * \overline{\Psi_r} \qquad (19)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_s^{'}L_r}\Psi_s\Psi_r \sin\gamma \qquad (20)$$

From the above condition, it is clearly identified that the torque generated is fluctuating between stationary flux and rotational flux i.e., γ. For achieving good dynamic performance fluctuation of γ should be as quick as possible. The flux in rotational part turns on in counter clockwise direction and increases steadily. However the flux in stationary part remains within the limit. By applying the suitable switching in the vector plane of voltage, torque and its fluctuation can be increased or decreased. Two vector planes with zero voltage state are connected to maintain the flux parameter in steady manner and also to marginally decrease the torque.

D. Switching of Space Vector Plane

The selected parameter control is based only on the switching of vector plane either in clockwise or anticlockwise direction to increase or decrease the flux of stationary part or torque respectively.

For suitable switching of vector plane to estimate the state of flux error in stationary part and torque error the below table is used.

Table- I: Voltage vector switching selection.

dΨe	dTe	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	-1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	1	V6	V1	V2	V3	V4	V5
0	-1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	1	V5	V6	V1	V2	V3	V4

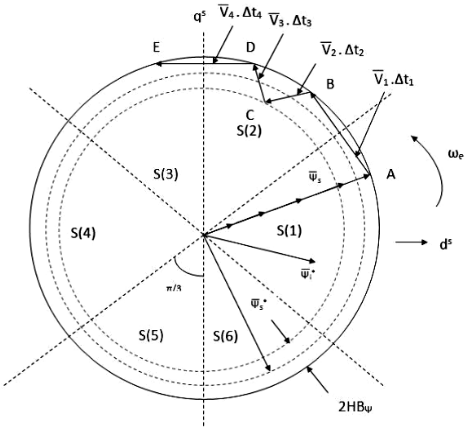

Fig. 2. Voltage Vector Plane.

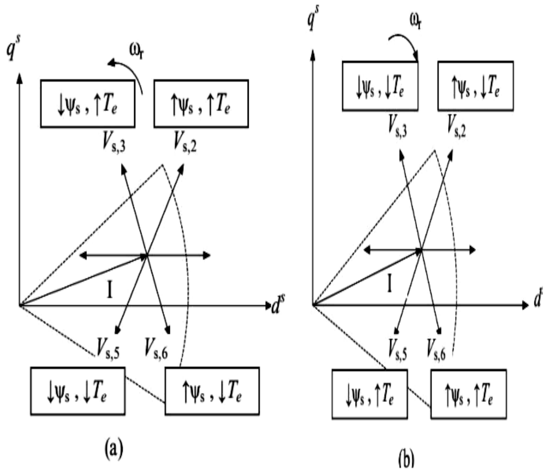

Fig. 3.Switching choices in
a) counterclockwise direction & b) clockwise direction.

E. Parameter Control using Hysteresis

The parameters whose reference values are compared with the evaluated values and the error are estimated. The estimated error is given to the controller having hysteresis operation.

$$h_f = 0 \; for \; F < F_{ref} + h_f$$
$$h_f = 1 \; for \; F < F_{ref} - h_f \qquad (20)$$
$$h_{Te} = 1 \; for \; T_e < T_{ref} - h_{Te}$$
$$T_{err} = 0 \; for \; T_e = T_{ref}$$
$$h_{Te} = -1 \; for \; T_e < T_{ref} + h_{Te} \qquad (21)$$

The Simulink representation of above mentioned controller block is shown as follows:

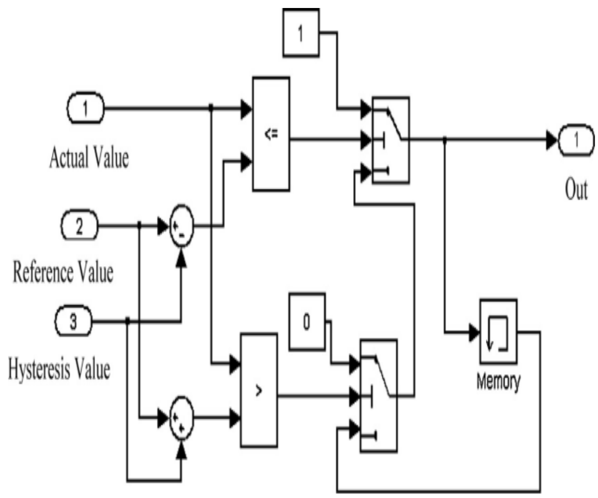

Fig. 4. Hysteresis Controller Block.

F. Results Analysis for SVPWM DTC

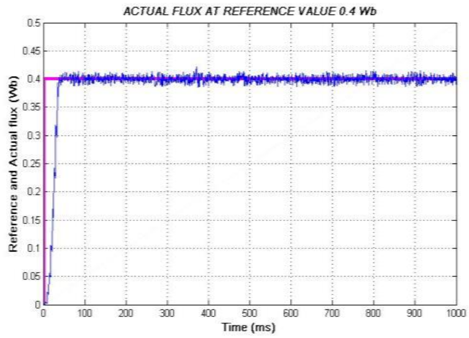

Fig. 5.Flux parameter estimated for reference flux at 0.4 wb.

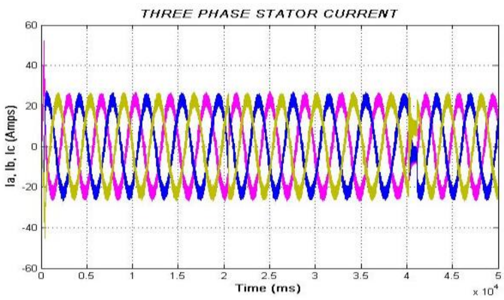

Fig. 6.Current in the Stationary part of IM.

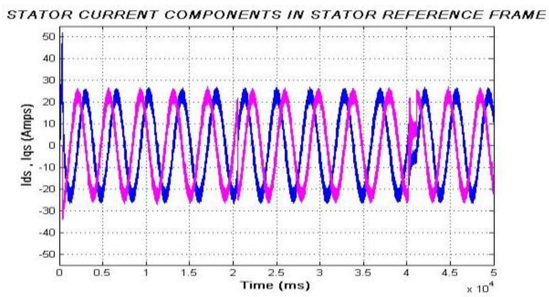

Fig. 7.Current components (Ids & Iqs) of the stationary part at standstill reference frame.

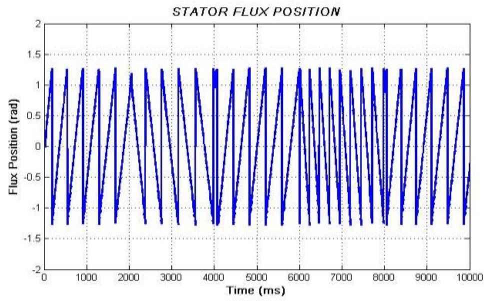

Fig. 8.Flux position of the Stationary part of IM.

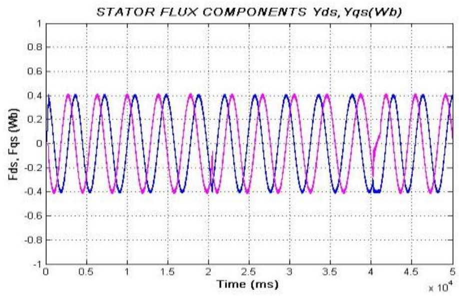

Fig. 9.Flux components (yds & yqs) of the stationary part at standstill reference frame.

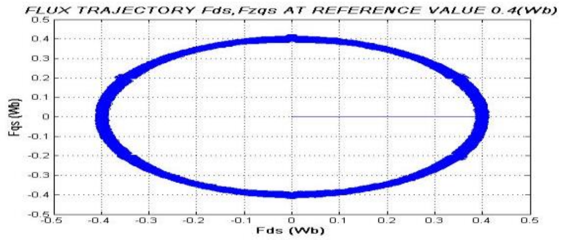

Fig. 10. Trajectory of Flux.

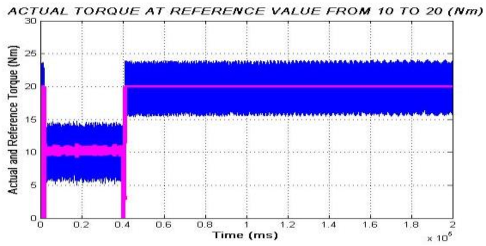

Fig. 11. Torque parameter estimated for reference torque of 10 to 20 Nm.

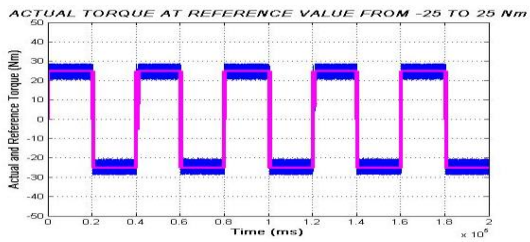

Fig. 12. Torque parameter estimated for reference torque of -25 to 25 Nm.

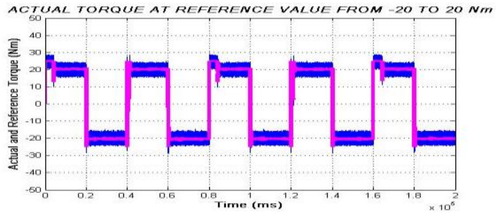

Fig. 13. Torque parameter estimated for reference torque of -20 to 20 Nm.

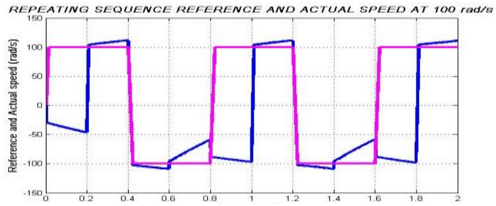

Fig. 14. Speed estimated for reference speed of 100 rad/sec.

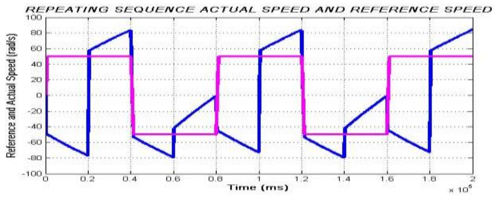

Fig. 15. Speed estimated for reference speed of 50 rad/sec.

Fig 5-15 shows the result of DTC drive for Induction motor under healthy condition. When a fault occurs under this condition, it does not behave in the same way which leads to failure of induction motor.

IV. FAULTS THAT AFFECTS HEALTHY CONDITION OF MACHINE

The major faults that changes the normal condition of the machine to damaged condition is listed as follows:

A. Fault Due to Open Phase

Fault occurs when any one supply phase voltage is removed where voltage supply must require three phase for normal working of motor. Due to this fault the motor could be burned or heat up.

B. Fault due to Unbalanced Voltage

By supplying voltage which is unbalanced in nature may result in negative sequence voltage. This may cause increased sequence currents both in positive and negative. Due to this fault the motor winding may get damaged due to excessive current flow.

C. Fault Due To Over Load

If the mechanical load applied to the motor is increased, then the motor consumes more current than usual and the winding gets heated up. Therefore the motor gets damaged.

D. Fault due to Over Voltage

The voltage supplied to the motor is more than the rated voltage for a certain period, this fault occurs. This increased voltage in the motor, may cause severe damage to the insulations provided.

E. Fault due to Under Voltage

The voltage supplied to the motor is less than the rated voltage for a certain period, this fault occurs. The motor consumes more current than usual and hence there will be no sufficient torque developed to achieve the normal operation.

V. PROPOSED INTELLIGENT MONITORING SYSTEM FOR MOTOR DRIVE

The monitoring of healthy and damaged condition of machine using MATLAB/Simulink is proposed with fuzzy based system. Fuzzy logic is a process of reminiscent thinking of human and regular dialect empowering choices to be made in view of ambiguous data. In this system, the current in the stationary part and time is considered as the prime input factors for the fuzzy monitoring system. The condition of motor (MC) is variable for fault identification and fault types (TF) for fault finding.

A. Fuzzy Rules Framing for Fault Identification

In major industries observing the status of motor drive is the most challenging one and also the vital requirement for retaining the performance. Here the system is advanced for observing the status of the DTC drive using one of the innovative computation method, fuzzy logic[5]. The current in the three phase stationary parts are predicted and taken as fuzzy system input. Also acquainting the time as second input factor. However, the motor will operate when fault occurs (If fault persisting time exceeds, the motor will fail). So time is considered here, which enhances the observing state of the detection system. The DTC induction motor drive performance is reviewed entirely under the actual running condition and comparing that with the performance under different fault supplied for a certain time period as mentioned above. This performance analysis is based on the consideration of DTC drive operation in which pulse generation is provided according to the predicted flux and torque. From the performance revision, the stationary part current for usual and unusual behavior are selected. Generally, induction motor faults are non-linear, fuzzy system is adopted with mamdani method. Based on which the input factors and output factors for fuzzy list is chosen and the membership function (Fuzzification) is designed. With this Fuzzy inference engine can able to observe the state of the machine for which we must to afford a proper defuzzification method, to attain the specified state of the machine as Seriously Damaged (0-30%), Damaged (25-75%), Good or Normal(70-100%) . Centroid method is adopted for the defuzzification. The input factors are the current in stationary parts which is represented in linguistic variable as {Big, Medium, Small, Zero} and for time {Long Duration and Short Duration}; the time is the very important factor because the fault occurring for long lifespan is very harmful to the machine. Therefore, the machine condition is depicted as Seriously Damaged, Damaged, and Good. By using these variables membership functions formed as follows:

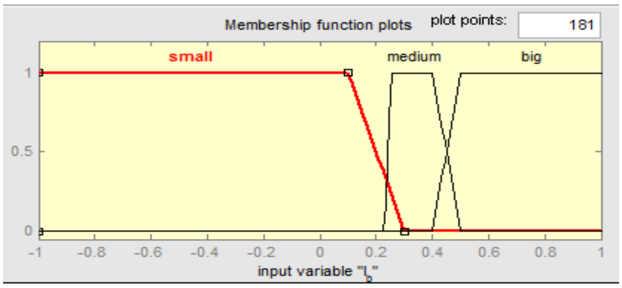

Fig. 16. MF for Ia, Ib, Ic.

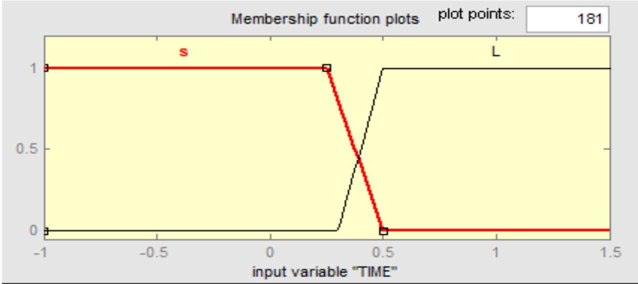

Fig. 17. MF for time duration.

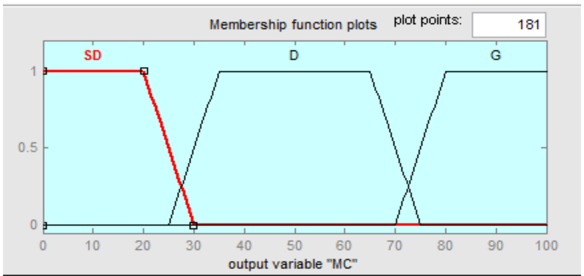

Fig. 18. MF for Machine Condition.

The major IF-THEN rules which predict all the faults are listed below as shown in Figure 19:

- If (I in A phase is Small) and (I in B phase is Small) and (I in C phase is Medium) and (time is Short Duration) then (CM is Good).
- If (I in A phase is Small) and (I in B phase is Medium) and (I in C phase is Medium) and (time is Long Duration) then (CM is Damaged).
- If (I in A phase is Medium) and ((I in B phase is Small) and (I in C phase is Medium) and (time is Long Duration) then (CM is Damaged).
- If (I in A phase is Medium) and (I in B phase is Medium) and (I in C phase is Medium) then (CM is Good).
- If (I in A phase is Small) and (I in B phase is Small) and (I in C phase is Small) then (CM is Good).
- If (I in A phase is Small) and (I in B phase is Medium) and (I in C phase is Small) and (time is Long Duration) then (CM is Damaged).
- If (I in A phase is Small) and (I in B phase is Small) and (I in C phase is Medium) and (time is Short Duration) then (MC is Good).
- If (I in A phase is Small) and (I in B phase is Medium) and (I in C phase is Medium) and (time is Long Duration) then (MC is Damaged).

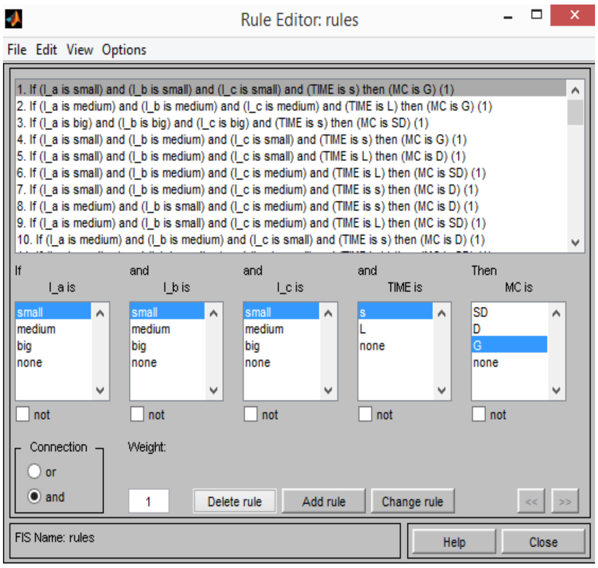

Fig. 19. Fuzzy Rule Toolbox in MATLAB.

B. Simulation Results

At the initially period after applying load to the DTC machine drive, the stationary part current increases abruptly and falls to the normal state. There may be a presence of transients in the current due to the controllers of DTC method.

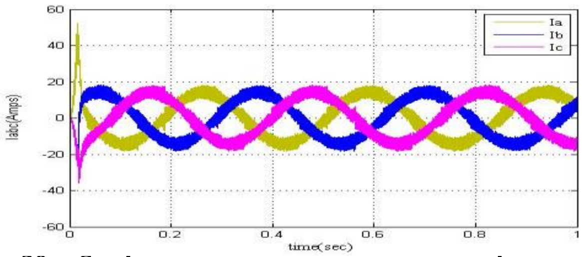

Fig. 20. Stationary part current response under normal state.

In order to illustrate the status of the machine, the current value after applying the load is examined along with the current rated and also for how long the that current occurs is linked in FIS. By analyzing the rules designed, the normal state of the machine is indicated by the defuzzified value of 89%.

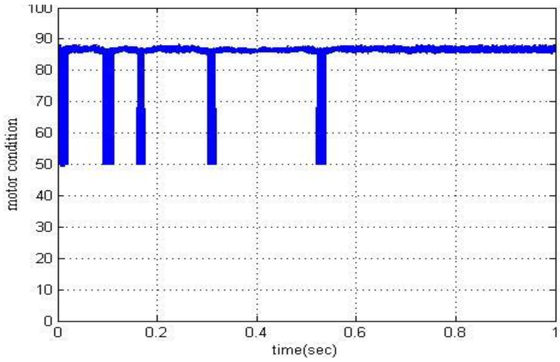

Fig. 21. Motor state under usual operation.

The supply voltage greater than the voltage rated for that machine is provided to the DTC drive will increase the stationary part current. If this continuous increase in current for an extended period causes severe damage to the machine. For 800 V supply voltage, the output current in stationary part is shown in figure 22.

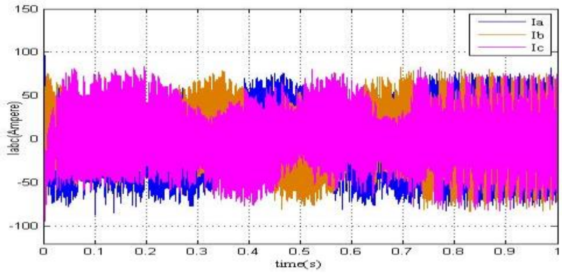

Fig. 22. Stationary part current response under over voltage condition.

For voltage greater than rated voltage, the current surpasses the rated current. If it continues for extended time interval then the motor state is seriously damaged with a decrypted value as 10-12% as shown in Figure 23.

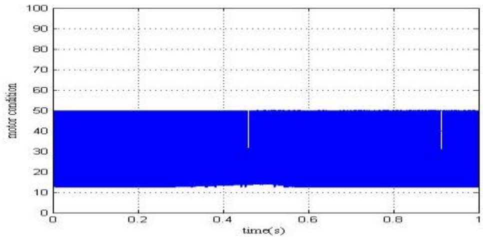

Fig. 23. Motor state for over voltage supply.

The supply voltage lesser than the voltage rated for that machine is provided to the DTC drive will decrease the stationary part current. If this continuous decrease in current for an extended period causes severe damage to the machine. For 50 V supply voltage, the output current in stationary part is shown in figure 24.

For voltage lesser than rated voltage, the current diminishes as that of the rated current. If it continues for extended time interval then the motor state is damaged with a decrypted value as 12-50% as shown in Figure 25.

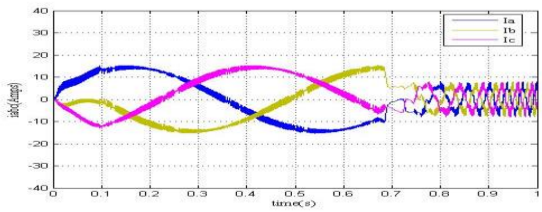

Fig. 24. Stationary part current response for under voltage condition

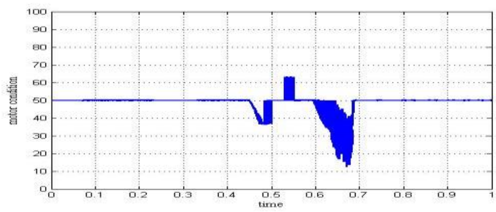

Fig. 25. Motor state for under voltage supply.

When the circuit is open, it causes the decrease in stationary part current which leads to damaged state of the motor. The output for open phase circuit in the drive is shown in Figure 26.

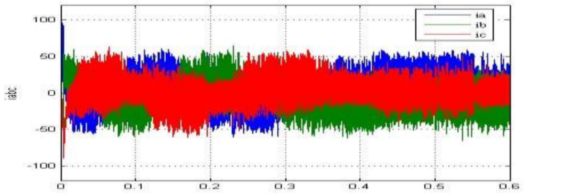

Fig. 26. Stationary part current response for open circuit conditions.

For open phase fault, the stationary part current is not as much of the rated current. If it withstand for extended time period then the motor gets damaged with respect to that of the decrypted value as 50-70% as shown in Figure 27.

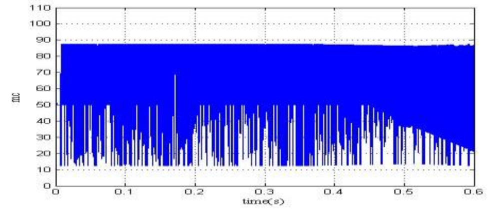

Fig. 27. Motor state for open circuit.

When the circuit is short, it causes increase in the stationary part current which leads to surpass the rated current which leads to critical state of the machine. The output for short circuit fault in the drive is shown in Figure 28.

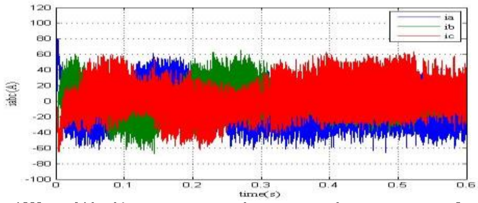

Fig. 28. Stationary part current response for short circuit condition

For short circuit fault, the stationary part current exceeds the current rated. If it withstand for extended time period then the motor gets damaged with a decrypted value as 50-70% as shown in Figure 29.

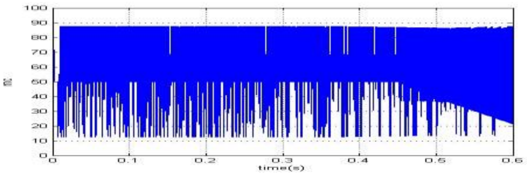

Fig. 29. Motor state for Short circuit.

VI. CONCLUSION

From the above result analysis, the inference made is that if the stator current is monitored continuously then the motor faults can be analyzed with the help of computational intelligence method such as fuzzy logic, neural networks with suitable drive setup and diagnosis can be done by maintaining the stator current in normal condition with the help of fuzzy systems

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