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A LITERATURE SURVEY ON FAULT INVESTIGATION METHODS OF VOLTAGE SOURCE INVERTERS

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Abstract: Industrial power electronics applications, Voltage source Inverter (VSI) has significant role including variable speed ac drives. But performance of the VSI degrades because of faults occur in it. One promising fault in inverter is open circuit transistor fault. Knowledge of fault mode is mostly important to improve performance of VSI. This paper discussed a literature survey on current methods for fault diagnosis and protection of switching transistors with unique focus on those used in three-phase power inverters. Finally, the capable methods are suggested for future work

***Index Terms* - Voltage source inverter, open circuit fault**

I. INTRODUCTION

Currently Industrial Power electronics technology has been broadly used in the areas of smart grids, new power generation, and rail traffic, of which Voltage Source Inverters (VSIs) play a most important role. Voltage source inverter has well-known characteristics as high performance, high accuracy, density, robustness and high reliability, VSI has been typically utilized in electric vehicles, aerospace, medical and military applications [1]–[6]. The failure of VSIs may result into shut down of industrial processes. Such shut down results into loss of efficiency, leads to security and green problems which disturbs the organization status. Thus, today's researchers have interesting research area on condition monitoring and fault diagnosis of three phases VSI

It has been observed that different types of faults can occurs in VSI, 38% faults in VSI are caused due to failure of power devices, electroctrolytic capacitors, and other electronic components [7]. The core components involved in power conversion are power switches such as Insulated Gate Bipolar Transistor (IGBT) or Metal Oxide Semiconductor Field Effect Transistor (MOSFET). Three phases VSI have six powers switches. The breakdown of these power switches can be mostly classified [8] as:

a. Short circuit fault (SCF),
b. Misfiring fault (MF) and
c. Open Circuit Fault (OCF).

The prime cause for the introduction of SCFs is caused by incorrect voltage levels at the gate terminal. One more reason for SCF could be an fundamental failure caused by overvoltage or avalanche stress. In the SCF, the VSI cannot be operated for a longer time and a repair is essential. The SCFs take place rapidly and IGBT can sustain against this fault for 10 µsec [9].Hence, it is hard to identify SCFs using algorithmic techniques as protection time is very small. There are hardware based protection circuits which are embedded in the integrated circuit and believed that switching devices are short circuit protected. MFs are caused due to missing transistor gate pulses which result in poor performance of devices. The electrical system can work with OCFs but system performance is drastically reduced .The OCFs can be diagnosed under partial fault working conditions of VSI without the stoppage of the system to avoid system failure. The most important purpose of this paper is to carry out a widespread survey of existing methods of fault diagnosis of open circuit fault of three phase voltage source inverter.

I. THREE PHASE INVERTER

Construction of three phases VSI using IGBTs are shown in Fig1. Three phase inverter is formed by connecting three single-phase inverters. To obtain three phase balanced voltages the gating signal has to be displaced by 120^0 with respect to each other. By forming arrangement of six transistors and six diodes a 3-phase output can be achieved. Two type of control signal can be applied to transistors; they are such as 180^0 or 120^0 conduction. Open circuit fault in T1 to T6 occur due to switches S1 to S6 respectively as shown in Figure. 1.

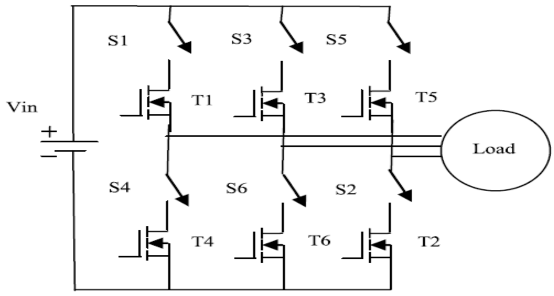

Figure 1: 3 ϕ PWM based Voltage Source Inverter

II. Fault Analysis

It is predicted that because of failure of power devices causes faults in variable speed ac drives. The majority of inverters use IGBTs because these power devices have characteristics as high voltage and current ratings and talent to handle short-circuit faults for periods exceeding 10 μs. Fault of IGBT can be mostly classified as diode open- faults, diode short-circuit faults, intermittent gate-misfiring faults, switch open and switch short fault that is shown in following figures .

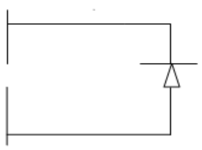

Figure 2: Diode open fault

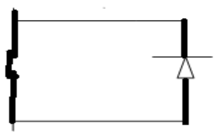

Figure.3: Diode short circuit fault

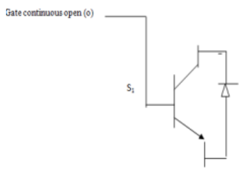

Figure 4: Gate open condition fault

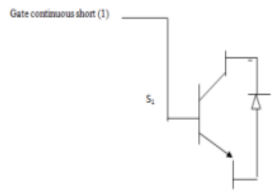

Figure 5: Gate Short condition fault

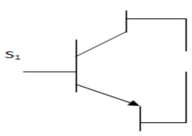

Figure 6 Fault due to the IGBT in open condition

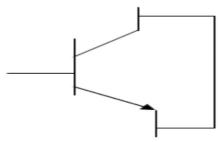

Figure 7 Fault due to the IGBT in Short condition

III CATEGORIZATION OF FAULT DIAGNOSIS METHODS

Currently, fault detection, diagnosis and prognosis are the major areas of research, fault detection means only indicating malfunction of system without pinpointing to particular fault. Fault diagnosis or isolation is to locate a particular fault in the system with finding root cause. Fault diagnosis estimates the size and nature of the fault. Fault prognosis is prediction of remaining useful life of a system component. Fault diagnostic systems are generally classified as Knowledge based systems, Model based systems, Signal based system, and Hybrid-Active fault diagnosis approach [17] as shown in Figure. 8

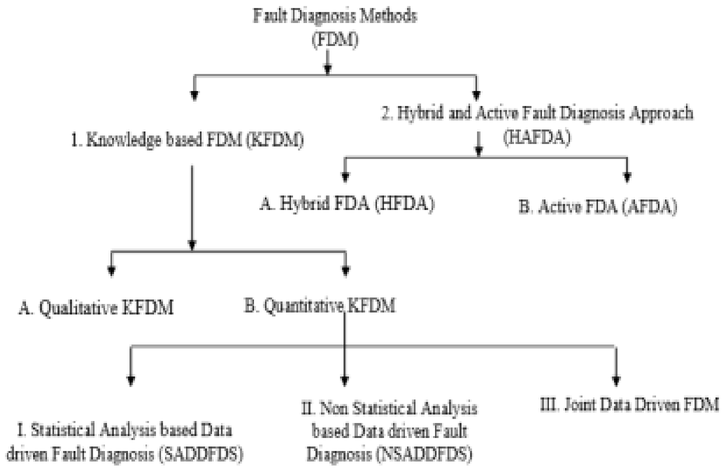

Figure8.Categorization of fault diagnostic methods

III.FAULT DETECTION METHODS

1) DQ transformation[16]:

The Construction of IGBTs in VSI is shown in Figure 1. The absolutely balanced three phase sinusoidal currents equations are shown below (1) in healthy operation of three phases VSI.

$$i_l = \begin{array}{c} I_R = I_m \sin(\omega_s t + \phi) \\ I_Y = I_m \sin(\omega_s t + \phi + \frac{2\pi}{3}) \\ I_B = I_m \sin(\omega_s t + \phi - \frac{2\pi}{3}) \end{array} \quad (1)$$

Where, I= R, Y or B, I_m is the highest amplitude of current $\omega_s t$ is current frequency and ϕ is the initial phase angle. Data packets are obtained by sensing three phase currents. Each data packet consists of gathering of samples for the angular frequency of 360^0 or one cycle. The maximum value of current that is I_m is obtained from these accumulated samples. The three phase currents are normalized within the range of ±1 to make the system load independent as:

$$i_M = \frac{i_l}{i_m} \quad (2)$$

The normalized 3 ϕ currents can also be obtained using equation (3)

$$i_{lm} = \begin{array}{c} i_{RM} = \sin(\omega_s t + \phi) \\ I_{YM} = \sin(\omega_s t + \phi + \frac{2\pi}{3}) \\ I_{BM} = \sin(\omega_s t + \phi - \frac{2\pi}{3}) \end{array} \quad (3)$$

The normalized 3 ϕ currents i_{lm} are not able to suppress high transients caused due to load variations. Parks Vector Modulus (PVM) method is used to overcome these high transients.

Three phase voltage inverter is simplified using the DQ transformation or Park's vector approach. It is mathematical conversion. This mathematical transformation, three phase current of inverter (I_R, I_Y and I_B) is converted into two phase current (i_d and i_q). And is identify by using following Equations. [16],

$$id = \sqrt{\frac{2}{3}} i_a - \frac{1}{\sqrt{6}} i_b - \frac{1}{2\sqrt{6}} i_c \quad (4)$$

$$i_q = \frac{1}{\sqrt{2}} (i_b - i_c) \quad (5)$$

Unique currents patterns for healthy and faulty conditions are obtained by using DQ transformation that is shown in Figure.8. For normal operation of switching transistors IGBT, pattern is a circle. In case of an open circuit IGBT fault; there are some emblematic patterns. From above mathematical analysis observed that with the help of DQ transformation can identify single switch open circuit fault. But these patterns are not helpful for multiple open circuit fault diagnosis. For that reason diagnostic variable and mean value of current are wanted to be taking into consideration for calculations.

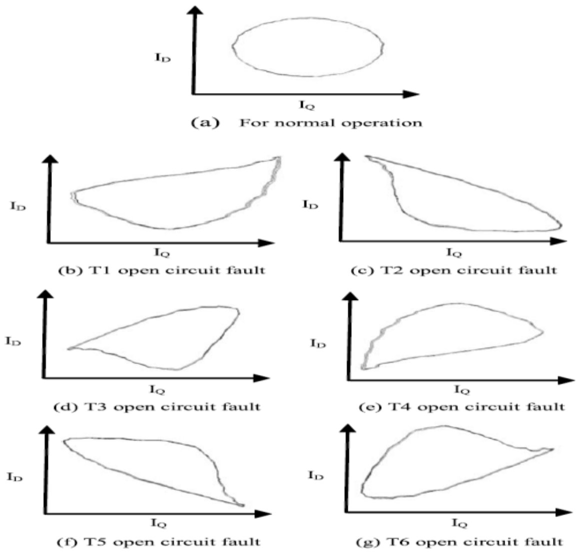

Figure 9: Different Current patterns for healthy and faulty conditions.

2) Multiple open switch fault diagnosis method:

In this technique, 3 ϕ current as input is necessary to apply. 3 ϕ voltage source inverter gives completely balanced three phase sinusoidal current under normal condition that is calculated by using Equation (6).

$$i_n = \begin{cases} i_p = I_m \sin(\omega_s t + \phi) \\ I_q = I_m \sin(\omega_s t - \frac{2\pi}{3} + \phi) \\ I_r = I_m \sin(\omega_s t - \frac{2\pi}{3} + +\phi) \end{cases} \qquad (6)$$

Where, n = p, q, r and I_m is the maximum amplitude of current, $\omega_s t$ is current frequency and ϕ is the initial phase angle. Normal Condition of the current of a VSI cannot identify by using equation (6)

2.1. Normalization of three phase currents

The problem of mechanical machine operating condition can be avoided using normalization of three phases current. With the help of output of DQ transformation i.e id and iq .can be identify normalization of current. Park's vector modulus ($|\bar{\imath}_s|$) can be obtained using following equation [16],

$$|\bar{\imath}_s| = \sqrt{i^2{}_d + i_q^2} \qquad (7)$$

Normalized three phase currents are obtained dividing three phase current of inverter by Park's vector modulus that is shown in below equation.

$$I_{nN} = \frac{i_n}{|i_s|} \qquad (8)$$

The Value of normalized phase currents of three phase inverter is of ±0.8164.

$$i_{nN} = \begin{cases} i_{pN} = \sqrt{\frac{2}{3}} \sin(\omega_s t + \phi) \\ I_{qN} = \sqrt{\frac{2}{3}} \sin(\omega_s t - \frac{2\pi}{3} + \phi) \\ I_{rN} = \sqrt{\frac{2}{3}} \sin(\omega_s t - \frac{2\pi}{3} + +\phi) \end{cases} \qquad (9)$$

Where n = p, q, r.

2.2. Average absolute values of normalized current:

With the help of three phase normalized current can be calculated average absolute values of normalized current by using Equation (10) [16],

$$\frac{\omega_s}{2\pi} \int_0^{\frac{2\pi}{\omega_s}} |i_{nN}| dt = \frac{1}{\pi} \sqrt{\frac{8}{3}} \qquad (10)$$

2.3. Diagnostic variables

Here, by using average absolute values of normalize three phase current can be calculated diagnostic variable. One diagnostic variable needs to be calculated for every phase. With the help of average absolute values of normalized current the errors can be calculated. Three diagnostic variables e_n (where, n = p, q, r) are calculated using these errors, that is specified by Equation (11) [14]. The e_n is calculated to generate fault diagnostic signature by Equations (15) to (16).

$$e_n = \xi - |i_{nN}| \quad (11)$$

Where ξ is a constant value. The value of ξ is equal to the average absolute value of the normalized phase currents of inverter under normal operating condition which is given by (10). Therefore for three phases, three constants are obtained as given in Equations (12–14).

$$\xi_p = 0.5144 \quad (12)$$

$$\xi_q = 0.5173 \quad (13)$$

$$\xi_r = 0.52b7 \quad (14)$$

In fault analysis diagnostic variables are enormously important. If diagnostic variable take approximately zero value that consider as healthy condition. If one of the diagnostic variable becomes positive that consider as faulty condition. If fault is introduced in switch, then diagnostic variable of phase, which contains that switch, takes positive value.

2.4. Average values of current

Fault phase are identify using Diagnostic variables. Diagnostic variables do not carry any information about the faulty switches. Therefore average current of three phases are used with diagnostic variables. Diagnostic variables detect faulty phase and average current identifies faulty switch from that faulty phase

$$E_n = \begin{Bmatrix} Negative\ if\ e_n < K_f \\ Positive\ if\ K_f \le e_n < k_d \\ Positive\ if\ k_d \le e_n \end{Bmatrix} \quad (15)$$

$$M_n = \begin{Bmatrix} Low\ if\ \langle i_{nN} \rangle < 0 \\ High\ if\ \langle i_{nN} \rangle < 0 \end{Bmatrix} \quad (16)$$

Where, E_n and M_n are diagnostic variable and average current respectively

Equations (15) and (16),E_n and M_n are used for fault diagnosis. K_d is used to identify two faulty switches in same phase, whereas K_f is used to detect two faulty switches in different phases. They are established by simply observing the behavior of E_n for various faulty conditions. Equations (15) and (16) create fault signatures as shown below;

$$IF\ (E1 =='\ Positive'\&\&\ E2 =='\ Negative'\&\&\ E3 =='\ Negative'\&\&\ M_a =='\ Low')$$
$$Then('T1\ is\ Faulty')$$
$$IF(E1 =='\ Posiitive'\&\&\ E2 =='\ Negative'\&\&\ E3 =='\ Negative'\&\&\ M_a\ =='\ High')$$
$$Then('T4\ is\ Faulty')$$
$$IF(E1 =='\ Positive'\&\&\ E2 =='\ Positive'\&\&\ E3 =='\ Negative'\&\&\ M_c\ =='\ High')$$
$$Then('T1\ \&\ T3\ are\ \ Faulty')$$

3) ***Wavelet-Fuzzy Algorithm [20]:***

This algorithm uses three phase current and can be used as a real-time condition-monitoring algorithm. Changes in current can be identifying using Wavelet analysis. The dc offset of current calculated by detecting a change of current. The open circuit and misfiring fault can be determined using fuzzy logic system. To distinguish between these faults, the period for which the offset exists is considered.

4) ***Wavelet-Neural Network Method [22]:***

This method is used to study the fault analysis of IGBT power inverter. Information about fault signature identified using Wavelet transform. The variation in decomposition coefficients contains this information. To discover the faulty and healthy mode normalized estimation of coefficients are fed into a back propagation artificial neural network (ANN) model .A diagnosis error is of less than 5% reported using simulation. A most important challenge is that of obtaining training data that covers the whole system state space for the faults of interest.

5) ***Wavelet-ANFI System [25]:***

For diagnosis of this method, the drive dc-link current is monitored over one cycle. With the help of continuous wavelet transform Adaptive Neuro fuzzy inference (ANFI) system is obtain. The fuzzy logic renders ability to build knowledge bases and the parameter adaptation enables learning of nonlinear behavior.

6) ***Model-Based ANN Diagnostic Method [11]:***

Model of a closed-loop motor drive is developed in this method. Multiclass of ANN was train using three-phase voltages, currents, and electromagnetic torque and that was provided by model of close loop motor drive . By using trained ANN can detect single-switch open-circuit faults and leg open faults in a three-phase inverter. By using this method near about 75% prediction rates for single switch open-circuit faults and above 90% for leg open faults are reported.

V PERFORMANCE PARAMETERS:

Performance of different fault diagnosis systems is evaluated based on parameters like effectiveness, fault detection time, implementation efforts, tuning efforts and resistivity against noise and load variation. All these parameters are given in brief as below.

• **Effectiveness (E):** Method is effective if it successfully point to the faulty switch. Effectiveness of the fault diagnosis systems is calculated using following equation

$$\text{Effectiveness}(\%) = \frac{\text{True Positive output}}{\text{Total Number of input samples}} X100 \qquad (17)$$

• **Fault Detection Time (FDT):** FDT is defined as time interval between instance of fault occurrence and instance of fault isolation.

• **Implementation Efforts (IE):** Implementation efforts of fault diagnosis system depend on the ease of sensing the detection parameter, packet size of data to be analysed, mathematical operation and decision making process.

• **Tuning Effort (TE):** For tunning effort should set low thresholds and tolerance value .

• **Resistivity against False Alarms (R):** Because of increased noise that is low signal to noise ratio false alarms may occur during light-load and transient conditions. The resistivity of fault diagnosis system is tested against noise and load variation.

Table 1: Comparison of Open Switch Fault Diagnosis Methods

Methods	Ref., Year	Effectiveness	Resistivity	Detection time	Implementation Effort	Tuning Effort	Capability to diagnose	Threshold Dependence
Park's Vector method	A. M. S. Mendes et. ali.,[10]	Uncertain at little currents	Very low at small currents	20.00 ms	Medium	High	Single switch fault	High
Normalized DC current Method	K. Rothenhagen. et. ali..[12]	Poor at few currents	Poor as multiple cond. may satisfy	18.40 ms	Low	Low	Single switch fault	Independent
Modified Normalized DC current method	K. Rothenhagen. et. ali.[13]	Good	Good	18.40 ms	Low	Low	Single switch fault	Independent
Slope method	R. Peuget. et. ali.[13]	Poor at small current	Poor	38.30 ms	Low	High	Single switch fault	High
Simple DC current method	A. M. S. Mendes et. ali.[11]	Cannot find faulty transistor	Medium	20.00 ms	Low	Medium	Single switch fault	High
Centriod based fault detection	R. B. Dhumale. et, ali. [17]	Good	Good	-	Medium	-	Single switch fault	N/A
Wavelet fuzzy Method	F. Charf et. ali.[22]	Good if and only if the fuzzy rules are charily designed	Good	5 cycles	High	Medium	Single switch fault	Low
Wavelet-Neural N/w	M. A. Awadallah et. ali.[[23]	Diagnosis error < 5%	Good if NN is thoroughly trained	-	High due to NN training	Low	Double switch fault	N/A
Wavelet-ANFI	Guan et. ali.[[25]	-	Good as the NN is trained for noisy condition	-	High due to NN training	Low	Double switch fault	N/A
Modelled based ANN method	A. M. S. Mendes et. ali.[11]	Prediction rate of around 75%	-	-	High	-	Double switch fault	N/A

Park' Vector and Fuzzy Logic	R. B. Dhumale. et, ali. [16]	If fuzzy rules are design accurately then effectiveness value is Good	Good	-	High	Medium	Single switch fault	Low
PVT, DWT and ANN	R. B. Dhumale. et, ali. [17]	-	Good	-	High	Medium	Single switch fault	Low
Park's Vector and Rule base	Zhang Jian-Jian. Et. ali., [15]	Good	Good	-	Medium	-	Single switch fault	N/A

VI CONCLUSION

In this paper various Methods of Fault diagnosis for voltage source inverter are compared. Faults in voltage source inverter are short circuit fault, Misfiring fault and open circuit fault. These methods normally based on 3Φ current transformation from time to other domain and classifier. For open circuit faults he modified normalized current method is found to be very effective in detecting faults with high resistivity to false alarms, and it is independent of load variations. Though open circuit fault found in one of the device then also the Current Deviation Method, has the advantage that it can take remedial measures and keep the inverter operate under a safe mode, as this method is embedded in the inverter control algorithm. Wavelet, fuzzy, and neural network-based methods turn into further intelligence for smart diagnosis of open circuit faults.

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