# AN EFFICIENT FAULT DETECTION ALGORITHM FOR BUCK CONVERTER FED BLDC MOTOR DRIVE 

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#### Abstract

Brushless dc (BLDC) motors are very prominent for majority of the applications because of their high reliability and simplicity. The detection and diagnosis of fault is required in advance for the implementation of fault-tolerant control (FTC) strategy. Thereby, even in the fault situation, the fault tolerant control of the motor is crucial. In this paper, an efficient fault detection control algorithm has been proposed for three phase full bridge inverter of BLDC motor. The proposed method control algorithm an able to identify and detect both the short circuit and open circuit faults. In order to isolate fault and further avoid the secondary fault various Protective measures are taken consideration. The simulation result, FUZZY logic controller is also implemented for speed control loop and comparison is made with PI and FUZZY speed controller.


Keywords: brushless dc (BLDC) motor, buck converter, fault tolerance, on-line fault diagnosis, fuzzy control, PI control.

## 1. INTRODUCTION

Electric drives are rapidly used in the modern world for various applications. The reliable operation of a typical electrical drive is essential for proper functioning of the entire system. A typical electric drive must be operating even in case of occurrence of the fault [1]-[2]. Fault-tolerant control (FTC) strategy is the fault diagnostic method to evaluation of the condition of fault including detection and necessary remedial measures to be taken to minimize the effect of the fault. The fault diagnostic methods include both online as well as offline. In case of BLDC drive system, the FTC is incorporated on the power inverter side [3]-[4]. FTC is gaining prominence in case of massive flow of current during fault in case of short circuit and voltage interruption in case of open circuit. Advancements in the FTC technology ranges in usage of time as well as frequency domain to update signal processing algorithm, although time domain is commonly used[5]-[6].

The reduction in the complexity of operation and quick detection facilitates the feasibility of time domain technique to be used in case of FTC. An algorithm based on measurement of electrical quantities and any deviation from the normal value might result in occurrence of fault [7]-[8]. In general, the electrical quantities considered are voltage of the motor or drive or current of the motor or drive [9]-[10]. If the fault occurs due to switching operation in case of DFIG system, the measured quantity (current or motor indicative characteristics) is compared with absolute theoretical value and the fault is detected based on the appropriate time domain FTC algorithm [11][12].

In case of failure of the proper operation of the switch, the detection variables are generally currents or voltages of the drive system which determine the drive characteristics [13]-[14]. The decision variables are monitored continuously to determine if there is any case of occurrence of the fault. These quantities may be corrupted with noise during the process of measurement and may result in fault alarm in case of operating current is low
[15]-[16]. There are various types of sensors which can detect the values of decision variables like measurement of line voltage, phase voltage are system model dependent methods, voltage of the pole of the inverter [17]-[18]. Moreover, the closed-loop ascendancy can could cause abate the accountability affection in the abstinent measurement values [19].

This paper proposes a model-based and low-cost switch fault diagnosis method for motor inverter composed of a buck converter and a three-phase full bridge. Based on the analysis of the faulty operating state in closed-loop control system, the residual signals of the voltage observers and the measurements are extracted to diagnose the inverter fault. The method can detect and identify both open-circuit and short-circuit faults fast accurate .The faults in buck converter and three-phase full bridge can be distinguished and protection measures are carried out to prevent the system from secondary fault. The proposed fault diagnosis algorithm is implemented in the existing control system as a subroutine. Finally, Result is presented to prove the validity and effectiveness of the proposed fault diagnosis method.

## 2. BUCK-CONVERTER FED BLDC MOTOR DRIVE -TEST SYSTEM

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Figure-1. Control system with` the proposed on-line diagnosis method.

Table-1 represents the BLDC drive specifications. Owing to minimum value of the torque constant and negligible effect of the rotor during state transition as the inertia of the rotor is a larger value, the steady state stability of the drive system is ensured. In case of FTC and other fault tolerant control methods, the parameter selection plays a crucial role. The threshold value is reached in case of the proposed method where values of $\mathrm{m}, \mathrm{n}, \mathrm{j}$ and q are taken as $0.25,1,4$ and 0.25 respectively. The fault control method for the buck converter fed BLDC motor drive system with protective circuit discussed in the paper is depicted in Figure-1.

Table-1. System ratings.

| Specifications | Quantity |
| :---: | :---: |
| Poles | 1 |
| Inertia | $0.00656 \mathrm{Kg} / \mathrm{m}^{2}$ |
| $\mathrm{~K}_{1}$ | $0.006 \mathrm{Nm} / \mathrm{A}$ |
| Ke | 120 Degree |
| R | 0.1 ohm |
| $\mathrm{L}_{\mathrm{a}}$ | $2.5 \mu \mathrm{H}$ |
| $\mathrm{U}_{\text {in }}$ | 28 V |
| Co | $5 \mu \mathrm{~F}$ |
| Lf | 1 mH |
| r | 0.045 ohm |
| $\mathrm{D} \Delta u_{\text {dio }}$, | 0.8 V |
|  |  |

The proposed electrical model is enacted in
Figure-2. The system equations in state space domain are given as
$\int \mathrm{u}_{0}=\mathrm{u}_{\mathrm{in}} \mathrm{d}_{1}-\Delta u_{d i 0}\left(1-\mathrm{d}_{1}\right)-\mathrm{L}_{\mathrm{f}} \frac{d_{i L}}{d t}-\mathrm{r}_{\mathrm{d} 7} \mathrm{i}_{\mathrm{L}} \mathrm{d}_{1}+w_{1}$

$$
\begin{equation*}
\mathrm{C}_{0} \frac{\mathrm{du}_{\mathrm{o}}}{\mathrm{dt}}=\mathrm{i}_{\mathrm{L}}-\mathrm{i} \tag{1}
\end{equation*}
$$

$$
\mathrm{u}_{0}=2 \mathrm{R}_{P} i+e_{L}+\Delta u_{d i o}
$$



Figure-2. The topology of buck-converter motor combinations.

Figure-2 shows the equivalent circuits under the normal and faulty case of single switch damage in threephase full bridge. We assume that the phase inductance of the ironless stator motor is negligible. The voltage equation of the BLDC motor can be represented as

$$
\begin{gather*}
\mathrm{u}_{\mathrm{d}}=u_{u}+\mathrm{ri}+w_{2-1 u} \\
\mathrm{u}_{1}=w_{2-1 l}+\mathrm{ri} \\
\mathrm{u}_{\mathrm{ul}}=2 R i+e_{L}+w_{2-2 u}+w_{2-2 l} \\
\mathrm{u}_{\mathrm{N}}=w_{2-2 l}+R_{p} i-e_{l o w}+w_{2-2 l}  \tag{2}\\
w_{2-1}=w_{2-1 u}+w_{2-2 l} \\
w_{2-2}=w_{2-1 l}+w_{2-2 u} \\
w_{2}=w_{2-1}+w_{2-2}
\end{gather*}
$$

Where $w_{2-1} \& w_{2-2}$ are perturbation signals due to occurrence of switch open circuit fault and short circuit faults in 3- $\phi$ full bridge. The $\mathrm{U}=$ Upper switch fault, $\mathrm{L}=$ Lower switch fault respectively.
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(a) $T_{7}$ is on

(b) $T_{7}$ is off.

Figure-3. The equivalent circuit of buck-converter motor combinations.

Figure-3. Two types of faults might not occur in the system. During open circuit fault, $w_{2}=w_{2-1}$ and $w_{2-2}=0$ and during switch short-circuit $w_{2}=w_{2-2}$ and $w_{2-1}=0$.

The possible system faults are
a) Open-circuit damage of converter switch $\left(F_{1}\right)$
b) Short-circuit damage of converter switch $\left(F_{2}\right)$
c) Open-circuit damage of single switch in bridge $\left(F_{3}\right)$
d) Short-circuit damage of single switch in bridge $\left(F_{4}\right)$

(a) Normal state

(b) Upper switch open-circuit fault state

(c) Lower switch open-circuit fault state

(d) Upper switch short-circuit fault state

(e)Lower switch short-circuit fault state.

Figure-4. Operating state under the normal and faulty cases of switch damage in three-phase full bridge.

From (1), the output voltage of buck converter can be simplified as
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$$
\begin{align*}
& u_{0}=\frac{L_{f}}{2 R_{p}} \frac{d u_{0}}{d t}-L_{f} C_{0} \frac{d^{2} u_{0}}{d t^{2}} \\
& =u_{i n} d_{1}-\Delta u_{d i o}\left(1-d_{1}\right)+\frac{L_{f}}{2 R_{p}} \frac{d e_{L}}{d t}+w_{1} \tag{4}
\end{align*}
$$

$u_{d}^{-}=2 R_{p} i+e_{L}$

$$
\left\{\begin{array}{c}
u_{1}+\frac{L_{f}}{2 R_{p}} \frac{d u_{1}}{d t}=u_{i n} d_{1}-\Delta u_{d i o}\left(1-d_{1}\right)-e_{L}+w_{1}  \tag{5}\\
u_{0}=u_{1}+e_{L}
\end{array}\right.
$$

$$
\mathrm{u}_{0}^{\dot{0}}=\frac{1}{1+T_{k} s}\left[u_{i n} d_{1}-\Delta u_{d i o}\left(1-d_{1}\right)-e_{L}\right]+e_{L}
$$

From (3), (4) Where $T_{k}=\frac{L_{f}}{2 R_{P}}$ satisfies. The discrete forms shown as

$$
\begin{align*}
& u_{0}^{-}(k)=\frac{T_{S}}{T_{S}+T_{k}}\left\{u_{i n} d_{1}(k)-\Delta u_{d i o}\left[1-d_{1}(k)\right]-e_{L}(k)\right\}+ \\
& \frac{T_{S}}{T_{S}+T_{k}} u_{1}(k-1)+e_{L}(k) \\
& u_{\mathrm{d}}^{-}(k)=2 R_{p}(k)+e_{L}(k) \tag{7}
\end{align*}
$$

The back EMF $e_{L}(k), e_{u p}(k), e_{\text {low }}(k)$, and $e_{u n}(k)$ can be given as
$e_{L}(k)=e_{\text {up }}(k)-e_{\text {low }}(k)$
$e_{u p}(k) \square=\left\{\begin{array}{c}w(k) f_{1}\left[\phi\left(k_{1}\right)\right] s t=1,3,5 \\ w(k) f_{1}\left[\frac{\pi}{3}-\phi\left(k_{1}\right)\right] s t=2,4,6\end{array}\right.$
$e_{\text {low }}(k)\left[\left\{\begin{array}{c}-w(k) f_{1}\left[\frac{\pi}{3}-\phi\left(k_{1}\right)\right] s t=1,3,5 \\ (10)\end{array} \quad-w(k) f_{1}\left[\phi\left(k_{1}\right)\right] s t=2,4,6\right.\right.$

$$
\begin{align*}
& e_{u n}(k) \text { 0 }= \\
& \left\{\begin{array}{c}
w(k) f_{2}\left[\phi\left(k_{1}\right)\right] s t=1,3,5 \\
w(k) f_{2}\left[\frac{\pi}{3}-\phi\left(k_{1}\right)\right] s t=2,4,6
\end{array}\right. \tag{11}
\end{align*}
$$

where $f_{1}(w t)$ and $f_{2}(w t)$ are the waveform function of the upper side phase and the unconducting phase back emf voltages when the operating state st is odd, $f_{1}(\omega t)$ and $f_{2}(\omega t)$ can be measured in the offline mode, $\left.e_{l( } k\right), e_{u p}(k)$, $e_{\text {low }}(k)$ and $e_{\text {un }}(k)$ are calculated online.
The estimated current electrical angle is given by

$$
\begin{equation*}
\phi\left(k_{1}\right)=w(k) T_{s}+\phi\left(k_{1}-1\right), k_{1} \geq 2 \tag{12}
\end{equation*}
$$

Where $\phi(1)=w\left(k-k_{1}+1\right) T_{1} \quad$ is $\quad$ achieved.
Also, $0 \angle \phi\left(k_{1}\right) \leq \frac{\pi}{3}$ should be achieved in order to avoid the estimation error caused by the motor velocity fluctuation.
Two residual signals are expressed as
$\xi_{1}=u_{0}^{-}=u_{d}+s_{1} \Delta u_{d l o}-u_{0}^{-}=w_{1}, w_{2}=0$
$\xi_{2}=u_{d}^{-}=u_{d}-u_{d}^{-}=w_{2}, w_{1}=0$

Where $s_{i}=1$ satisfies when $I>0, s_{i}=0$ satisfies. The fault identification signals are expressed as

$$
\begin{align*}
& \xi_{3}=u_{d}-2 u_{N}-e_{u p}-e_{l o w}+\Delta u_{u n}  \tag{15}\\
& =w_{2-2 u}+w_{2-1 u}-w_{2-2 l}-w_{2-1 l}+\Delta u_{u n} \\
& \xi_{4}=\operatorname{sgn}\left(i_{u p}^{-}\right)+\operatorname{sgn}\left(i_{l o w}^{-}\right) \tag{16}
\end{align*}
$$

From (6) (7), where $u_{N}$ is the motor neutral voltage, satisfying can be calculated from the phase voltage of the unconducting phase which may abnormally conduct through the diode of upper or lower switch after the fault of $F_{4} . U_{u n}$ can be calculated through

$$
\left\{\begin{array}{c}
-\Delta u_{D 2} u_{N}+e_{i n}<\Delta u_{D 2}  \tag{17}\\
u_{d}+\Delta u_{D 5} u_{N}+e_{i n}>\Delta u_{D 5} \\
u_{N}+e_{u n}-\Delta u_{D 2} \leq u_{N}+e_{i n} \leq e_{d}+\Delta u_{D 5}
\end{array}\right.
$$

The signal $\xi_{4}$ can reflect the symbolic of the estimated phase currents which are given as
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$\left\{\begin{array}{c}\mathrm{i}_{\mathrm{up}}^{-}=\left(u_{d}+u_{N}+e_{u p}\right) / R_{p} \\ i_{\text {low }}^{-}=\left(u_{N}+e_{\text {low }) / R_{P}}\right.\end{array}\right.$
$\xi_{1}$ and $\xi_{2}$ are used to detect the fault type $\mathrm{F} 1 \sim \mathrm{~F}_{2} \xi_{3}$ and $\xi_{4}$ are used to identify the faulty switch of fault type F4.

## 3. ANALYSIS OF INVERTER FAULT FEATURE

Four kinds of single switch fault are analyzed in this section.

## A. Switch open-circuit fault in buck converter

From (11), (12) During fault $F_{1}, T_{7}$ is in off condition, $i_{L}$ becomes to null value due to presence of reactive elements in the converter circuit. The current of the motor tend to reduce to zero and output voltage will reach to normal value, i.e., back EMF.The condition of fault results in reduction in current as well as velocity of the drive to decrease. The predicted value of output is same as input. The implementation of closed loop control results in satisfying the condition $\xi_{1}<0$. Also $\xi_{2}=0$ as is possible the fault fails to create any impact on the operating state of the full bridge converter.

## B. Switch short-circuit fault in buck converter

From (14), (15) $F_{2}$ forces $\mathrm{T}_{7}$ to ON . Then the sequence of events is similar to the previous condition, the voltage at the output terminals along with the current through the inverter will increase where the voltage will be numerically similar to the input voltage. The rest is same as previous operation.

## C. Switch open-circuit fault in three-phase full bridge

$F_{3}$ occurrence tend to reduce the link current to zero and the voltage of the output of buck converter is given as

$$
\left\{\begin{array}{c}
u_{0}+L_{f} C_{o} \frac{d^{2} u_{0}}{d t^{2}}=u_{i n} d_{1}-\Delta u_{d i o}\left(1-d_{1}\right)  \tag{19}\\
\mathrm{C}_{0} \frac{\mathrm{du}_{o}}{\mathrm{dt}}=\mathrm{i}_{\mathrm{L}}
\end{array}\right.
$$

## D. Switch short-circuit fault in three-phase full bridge

Form (17), (19) Figure-5 depicts the alternate path for the flow of current through phase which is not conducting. The voltage fed to the motor fed during two operating states in terms of three phase voltages is given by
$u_{d}=\frac{\left[3 R_{P} i+\left(e_{B}-e_{C}\right)+\left(e_{A}-e_{C}\right)\right]}{2}$
$u_{d}=\frac{\left[3 R_{P} i+\left(e_{B}-e_{C}\right)+\left(e_{A}-e_{C}\right)-\Delta u_{D 3}-r i_{B}\right]}{2}$
$\varepsilon_{2}<0$ can be easily achieved as seen from (8), (21)and (22). Due to closed loop control, post fault voltage will decrease due to abnormal current flow. If the load change is neglected, $\xi_{1}<0$ may be achieved. The switching of transistors will be determined by rotor position. The dead short path is given in Figure-4 and cause over current although the time duration of over current is less due to closed loop results in $d_{1}$ to be zero. The abnormal current cannot create impact on any of the phases.


Figure-5(a). $u d>u B$.


Figure-5(b). $u d<u_{B}$
Figure-5. Currentpathsunder $T_{1}$ short-circuit fault when $s t=3$.

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Figure-6. The abnormal conducting of the complete shortcircuits of the limb caused by the fault of $F 4$.

The equivalent circuit is shown in Figure-6. The output voltage of the buck converter is given as

$$
\left\{\begin{array}{c}
\mathrm{u}_{0}=-\mathrm{L}_{\mathrm{f}} \frac{d_{i L}}{d t}-\Delta \mathrm{u}_{d l o}  \tag{22}\\
\mathrm{C}_{0} \frac{\mathrm{du}_{\mathrm{o}}}{\mathrm{dt}}=\mathrm{i}_{\mathrm{L}}-\mathrm{i} \\
\mathrm{u}_{0}=\mathrm{r} i+\Delta u_{d i o}
\end{array}\right.
$$

From (5), a second order differential equation can be deduced as

$$
\begin{equation*}
\frac{d^{2} u_{0}}{d t^{2}}+\frac{1}{C_{0} R} \frac{d u_{0}}{d t}+\frac{1}{L_{f} C_{0}} u_{0}=\frac{1}{L_{f} C_{0}} u_{d i o} \tag{23}
\end{equation*}
$$

Using the initial values of $\mathrm{u}_{0}(\mathrm{t}=0)=\mathrm{U}$ and, $\mathrm{u}_{0}(\mathrm{t}=0)=-\left(\mathrm{U}-\Delta u_{\text {dio }}\right) / C_{0} r$ the time interval $t_{1}$ of the output voltage of the buck converter $u_{0}$ decreases from the initial value $U$ to $\Delta u_{d i o}$ can be calculated as

$$
\begin{equation*}
\mathrm{t}_{1}=\mathrm{r} \cdot \mathrm{C}_{0} \tag{24}
\end{equation*}
$$

From (23), (24) $\mathrm{t}_{1} \leq 1 \mu$ sis possible from Table-1. The post fault output voltage becomes zero fast and $\xi_{1} 1<$ 0 and $\xi_{2}<0$ are achieved. The effect of $F_{4}$ is weakened by the existence of the buck converter and current loop controller. Sudden influx of current as pictured in Figure5(a) and (b) is back EMF at very high speed. When phase C is notconducting, the voltage equations of the two conducting phases and the neutral voltage are expressed as:

$$
\begin{align*}
& \left\{\begin{array}{c}
\mathrm{u}_{A}=u_{d}-\Delta u_{r 1}=\Delta u_{r 4} \approx 0 \\
u_{B}=u_{d}+\Delta u_{D 3}
\end{array}\right.  \tag{25}\\
& u_{N}=\frac{\left(u_{d}+\Delta u_{D 3}-e_{A}-e_{B}\right)}{2} \tag{26}
\end{align*}
$$

The actual phase currents of the upper side and lower side are expressed as

$$
\left\{\begin{array}{c}
\mathrm{i}_{\text {up }}=i_{B}=\left(u_{d}+\Delta u_{D 3}+e_{B}-u_{N}\right) / R  \tag{27}\\
i_{l o w}=-i_{A}\left(e_{N}+u_{N}-u_{d}\right) / R_{p}
\end{array}\right.
$$

When Phase C is conducting through the diode $\mathrm{D}_{2}$ the neutral voltage is expressed as
$u_{N}=\frac{\left(u_{d}-e_{A}-e_{B}-e_{C}\right)}{3}$

From (9) and (10). Also, when phase C is conducting through the diode $D_{5}$, the neutral voltage is expressed as
$u_{N}=\frac{\left(2 u_{d}+2 \Delta u_{D 3}-e_{A}-e_{B}-e_{C}\right)}{3}$

From (25), (26), (31) Figure-5(b) shows the short-circuit fault which happens in lower switch T4during $s t=1$. Similarly, when phase C is not conducting, the two conducting phase voltages and the neutral voltage satisfy

$$
\begin{align*}
& \left\{\begin{array}{c}
\mathrm{u}_{A}=\Delta u_{T 4} \approx u_{d} \\
u_{B}=-\Delta u_{D 6}
\end{array}\right.  \tag{30}\\
& u_{N}=\frac{\left(u_{d}-\Delta u_{D 6}-e_{A}-e_{B}\right)}{2} \tag{31}
\end{align*}
$$



Figure-7(a). The complete short-circuit of the limb caused by $T 1$ fault when $s t=4$.


Figure-7(b). The complete short-circuit of the limb caused byT4fault when $s t=1$.

Figure-7. Current paths under the faulty case of fault type $F_{4}$.

The actual phase currents of the upper side and lower side are expressed as
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$\left\{\begin{array}{c}\mathrm{i}_{\mathrm{up}}=i_{A}=\left(u_{d}-e_{A}-u_{N}\right) / R \\ i_{\text {low }}=-i_{B}\left(e_{B}+u_{N}-\Delta u_{D 6}\right) / R\end{array}\right.$
When phase C is conducting through the diode $D_{2}$, the neutral voltage is expressed as
$u_{N}=\frac{\left(u_{d}-\Delta u_{D 6}-e_{A}-e_{B}-e_{C}\right)}{3}$

When phase C is conducting through the diode $D_{5}$, the neutral voltage is expressed as
$u_{N}=\frac{\left(2 u_{d}-e_{A}-e_{B}-e_{C}\right)}{3}$

## 4. FAULT DIAGNOSIS AND PROTECTION

## A. Fault detection

From (33), (36), (37) Figure-7. In case of $F_{1}$ or $F_{2}$, the fault feature will show in $\varepsilon_{1}$ only. If $F_{3}$ or $F_{4 t}$ type of fault happens, the fault feature will show in both $\varepsilon_{1}$ and $\varepsilon_{2}$. Thus, $F_{3}$ and $F_{4}$ should be detected only by the fault feature $\varepsilon_{2}$ at first.

At first, the detection of fault type $F_{4}$ and the complete short-circuit of the limb caused by fault type $F_{4}$ are achieved by
$t_{f 4}=\left\{\begin{array}{r}0, \varepsilon_{2}>e_{t h 2^{\prime} s} \\ t_{f 4+T_{s}}, \varepsilon_{2} \leq e_{t h 2_{-} s}\end{array}\right.$
$t_{f 4 s}=\left\{\begin{aligned} 0, & G_{4}=0 \\ t_{f 4 s+T_{s}}, & G_{4}=1, \varepsilon_{4}=-2\end{aligned}\right.$
$t_{f 3}=\left\{\begin{array}{r}0, \varepsilon_{2}>e_{t h 2_{-} o} \\ t_{f 3+T_{s}}, \varepsilon_{2} \geq e_{t h 2_{-} 0}\end{array}\right.$
From (38) where $\mathrm{t}_{\mathrm{f}}$ denoted the fault detection time of fault type $\mathrm{F}_{3}$. After the detection of no switch fault in three phase full bridge the fault type $F_{2}$ and $F_{1}$ can be detected by
$t_{f 2}=\left\{\begin{array}{r}0, \\ , \varepsilon_{2}>e_{t h 1 \_s} \\ t_{f 2+T_{s}}, \\ \varepsilon_{2} \leq e_{t h 1 \_s}\end{array}\right.$
$t_{f 1}=\left\{\begin{array}{r}0, \varepsilon_{1}>e_{t h 1 \_0} \\ t_{f 1+T_{s}}, \varepsilon_{1} \leq e_{t h 1_{\_} 0}\end{array}\right.$
$G_{x}=\left\{\begin{array}{l}1, t_{f x} \geq T_{\text {fault }} \\ 0, \\ t_{f x}<T_{\text {fault }}\end{array}\right.$

From (38), (39), (40) Where $\mathrm{T}_{\text {fault }}$ is fault detection time and given by $\mathrm{T}_{\text {fault }}=\mathrm{k}_{\mathrm{t} .} \cdot \mathrm{T}_{\mathrm{s}}, \mathrm{G}_{\mathrm{x}, \mathrm{X}}$ represents fault flag status $1,2,3,4$, and 4 s respectively. The value of $\mathrm{k}_{\mathrm{tf}}$ is decided keeping in mind both the detection time and
robustness against false detection. The threshold value of and in (18) and (20) are chosen.
$t_{f 1}=\left\{\begin{array}{l}e_{t h 1-0}=-m\left(u_{i n}-E\right) \\ e_{t h 1-0}=m m\left(u_{i n}-E\right)\end{array}\right.$
The actual input voltage of the motor is given as
$u_{d}=\left(R_{P}+R+R_{2}\right) i+e_{L}+\Delta u$


Figure-8. Flowchart of the proposed on-line diagnosis method.

From (41), (42) Thus, the threshold values are given by

$$
\begin{align*}
& e_{t h 2_{-} 0}=0.5 n \frac{T_{s}}{C_{0}}\left(i_{\text {ref }}+i\right), n>0  \tag{43}\\
& e_{\text {th2_s }}=-0.5 j R\left(i_{\text {ref }}+i\right), j \geq 0.5 \tag{44}
\end{align*}
$$

$\xi_{4}=s\left(i_{\text {up }}^{-} k\right)-s\left(i_{\text {low }}^{-}\right)$

Where the function $s(x)$ is expressed as
$s(x)=\left\{\begin{array}{c}1, x>\Delta z \\ 0,-\Delta z \leq x \leq \Delta z A=\pi r^{2} \\ -1, x<-\Delta z\end{array}\right.$
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From (43), (44), (45), (46), (47) The dead zone $\Delta z$ is chosen to be $\Delta z=q i_{r e f}$, where $0<q<1$ is satisfied. The value of $q$ should be carefully selected to minimize the possibility of false error detection. If $q$ is selected too high, the complete short-circuit of the limb caused by fault of F4may not be detected. Moreover, if $q$ is too small, the probability of false error detection increases.

Figure-8: The faulty switch in three-phase full bridge should be identified after the detection of the fault type $F_{3}$ and $F_{4} . \varepsilon_{3}$ is chosen to identify the faulty switch. The fault identifying flag of single switch in three-phase full bridge is given as

$$
G_{1}=\left\{\begin{array}{l}
1, \varepsilon_{3}>0  \tag{47}\\
-1, \varepsilon_{3}<0
\end{array}\right.
$$

## B. Fault identification

Table-2. Fault Identification Algorithm.

| Fault type | Faulty switch | G3 | G4 | G1 | G5 | Current state |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| F3 | T1 | 1 | 0 | 1 | 0 | st $=1$ or 2 |
|  | T2 | 1 | 0 | -1 | 0 | $\mathrm{st}=2$ or 3 |
|  | T3 | 1 | 0 | 1 | 0 | st $=3$ or 4 |
|  | T4 | 1 | 0 | -1 | 0 | st $=4$ or 5 |
|  | T5 | 1 | 0 | 1 | 0 | st $=5$ or 6 |
|  | T6 | 1 | 0 | -1 | 0 | st $=1$ or 6 |
| F4 | T1 | 0 | 1 | -1 | 0 | st $=3$ or 6 |
|  |  | 0 | 1 | -1 | 1 | st $=4$ or 5 |
|  | T2 | 0 | 1 | 1 | 0 | st $=1$ or 4 |
|  |  | 0 | 1 | 1 | 1 | st $=5$ or 6 |
|  | T3 | 0 | 1 | -1 | 0 | st $=2$ or 5 |
|  |  | 0 | 1 | -1 | 1 | st $=1$ or 6 |
|  | T4 | 0 | 1 | 1 | 0 | st $=3$ or 6 |
|  |  | 0 | 1 | 1 | 1 | st $=1$ or 2 |
|  | T5 | 0 | 1 | -1 | 0 | st $=1$ or 4 |
|  |  | 0 | 1 | -1 | 1 | $\mathrm{st}=2$ or 3 |
|  | T6 | 0 | 1 | 1 | 0 | st $=2$ or 5 |
|  |  | 0 | 1 | 1 | 1 | st $=3$ or 4 |

The value of $\varepsilon_{3}$ will be analyzed in detail for the upper switch open-circuit fault, lower switch open-circuit fault, upper switch short-circuit fault and lower switch short-circuit fault respectively.

## i. Upper switch open-circuit fault in three-phase full bridge

From (2) and (16), $\varepsilon_{3}=w_{2-1 u}$ is possible if fault occurs in upper switch. Since the fault $F_{3}$ will cause the output voltage of buck converter increase, $u_{d}>u_{u}$ satisfies. Thus, $\varepsilon_{3}>0$ is achieved from (2).

## ii. Lower switch open-circuit fault in three-phase full bridge

$\varepsilon_{3}=-w_{2-11}$ is achieved when the lower switch open-switch fault happens. $\varepsilon_{3}<0$ is achieved from (2).

## iii. Upper switch short-circuit fault in three-phase full bridge

From (2), $\varepsilon_{3}<0$ is achieved since $\varepsilon_{3}=w_{2-2 u}$ and $\varepsilon_{2}=$ $w_{2}=w_{2-2 u}<0$ are obtained when the short-circuit fault occurs in complementary switch, $\varepsilon_{2}<0$ and $\varepsilon_{4}=-2$ can be detected. Substituting (27), (29) and (30) into (16) respectively, can be deduced. Thus, $\varepsilon_{3}<0$ is used to identify the upper side switch short-circuit fault.

## iv. Lower switch short-circuit fault in three-phase full bridge

$\varepsilon_{2}=w_{2}=w_{2-2 l}<0$ is occurs due to fault in lower switch. Similarly, $\varepsilon_{3}=-w_{2-21}>0$ and can be obtained from (2), (16), (32), (34) and (35). Thus, $\varepsilon_{3}>0$ is used to identify the faulty switch.

## C. Fault protection

## i. Switch open-circuit fault in three-phase full bridge

After fault diagnosis of $F_{1}, T_{7}$ is switched off and $T_{8}$ is switched on with certain duty circle to discharge the
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high output voltage of buck converter in the faulty operating state in order to avoid the secondary fault.

## ii. Switch short-circuit fault in three-phase full bridge

After the fault diagnosis of $F_{4}$, the complementary switch of the faulty one is cut off and the relay connected in series in the circuit of the faulty phase winding is used to isolate the faulty phase.

## iii. Switch short-circuit fault in buck converter

After the fault diagnosis of $F_{2}$, the dc-link input voltage supply should be cut off immediately.

## iv. Fuzzy controller

Figure-9. Fuzzy logical controller is an advanced controlled using multi valued logical. It is works on the principle of rule based system. It involves two processes namely fuzzification and defuzzication. The inputs to the fuzzy logic controller are speed error and rule of change of speed error and output is reference torque.


Figure-9. Block diagram of fuzzy logic controller.


Figure-10. Simulink diagram of fuzzy logical control.
Figure-10 show simulink diagram implementation of Fuzzy logic controller (FLC). The following are various linguistic terms for the FLC:

- Negative Big (NB)
- Negative Medium(NS)
- Zero (Z)
- Positive Medium (PM)
- Positive Big (PB)

The input and output membership functions are shown in Figure-11and Figure-12 and Figure-13 respectively.


Figure-11. Membership functions for input error.
Table-3. Rule base for Fuzzy Controller for 6-switch three phase VSI fed speed control drive PMBLDC motor.

| Error/cerro <br> r | NB | $\begin{aligned} & \hline \mathbf{N} \\ & \mathbf{M} \end{aligned}$ | NS | Z | PS | $\begin{gathered} \mathbf{P} \\ \mathbf{M} \end{gathered}$ | PB |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| NB | NB | NB | NB | NB | $\begin{aligned} & \mathrm{N} \\ & \mathrm{M} \end{aligned}$ | NS | Z |
| NM | NB | NB | NB | $\begin{aligned} & \mathrm{N} \\ & \mathrm{M} \\ & \hline \end{aligned}$ | N | Z | PS |
| NS | NB | NB | $\begin{aligned} & \hline \mathrm{N} \\ & \mathrm{M} \\ & \hline \end{aligned}$ | NS | Z | PS | $\begin{gathered} \hline \mathrm{P} \\ \mathrm{M} \\ \hline \end{gathered}$ |
| Z | NB | NM | NS | Z | PS | PM | PB |
| PS | $\begin{aligned} & \hline \mathrm{N} \\ & \mathrm{M} \\ & \hline \end{aligned}$ | NS | Z | PS | PM | PB | PB |
| PM | NS | Z | PS | PM | PB | PB | PB |
| PB | Z | PS | PM | PB | PB | PB | PB |



Figure-12. Membership functions for change in 'cerror.
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Figure-13. Membership function of output variable.
From Table-3, Fuzzy Rule base: The set of linguistic rules is the essential part of a fuzzy controller. In many cases it's easy to translate an expert's experience into these rules and any number of such rules can be created to define the actions of the controller. In the designed fuzzy system, conventional fuzzy conditions and relations k is C " are used Cerror is B , then $\Delta$ such as "If e is A and to create the fuzzy rule base ( $7 \times 7$ ).

## 5. SIMULATED RESULTS

A. Simulation result of switch fault in BUCK converter by using PI controller


Figure-14. Switch fault in buck converter by considering open circuit fault.


Figure-15. Switch fault in Buck Converter by considering Short circuit fault.

The reproduced aftereffects of finding procedures of issue $F_{1}$ and $F_{2}$ at the rotor pace of $5000 \mathrm{r} / \mathrm{min}$ are appeared in Figure-14 and Figure-15. The switch opencircuit shortcoming was embedded through the FPGA by the perpetual off sign of the door driver. Thus, the switch cut off was displayed by turning the door flag forever on. The event of the issue conditions $F_{1}$ and $F_{2}$ are indicated by the banners $\mathrm{G}_{10}$ and $\mathrm{G}_{20}$. $\varepsilon_{1}, \mathrm{e}_{\text {th1_s }}$ and $\mathrm{e}_{\text {th1_o }}$ are produced to recognize the issue. $G_{1}$ and $G_{2}$ denote the shortcoming analysis banners of issue $F_{1}$ and $F_{2}$.
B. Simulation results of switch fault in three phase full bridge by using PI controller


Figure-16. Switch fault in three-phase full bridge $\mathrm{T}_{1}$ open circuit fault.
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Figure-17. Switch fault in three-phase full bridge $\mathrm{T}_{4}$ open Circuit fault.

In the proposed technique, $\mathrm{ktf}=5$ is picked. It can be learnt that with the recreations and investigations. From the reenacted, the issue analysis time of short out shortcoming and open-circuit issue in buck converter are demonstrated as 0.001 s and 0.003 s individually. The reenactment consequences of the conclusion procedure of issue F3and F4are appeared in Figure-15 and Figure-16. Figures 17, 18, and Figures 19, 20 demonstrate the mimicked analysis consequences of issue $\mathrm{F}_{3}$ with the proposed technique. The event of the deficiency condition $\mathrm{F}_{3}$ is meant by the banner $\mathrm{G}_{3}$. In the proposed conclusion technique, $\varepsilon_{2}$ and $\mathrm{e}_{\mathrm{th} 2 \_\mathrm{o}}$ are created to recognize the opencircuit issue. $\varepsilon_{3}$ is used to distinguish the defective switch by the rationale appeared in Table-2.


Figure-18. Switch fault in three-phase full bridge $\mathrm{T}_{1}$ Short Circuit fault $\mathrm{St}=4$.


Figure-19. Switch fault in three-phase full bridge $\mathrm{T}_{1}$ Short Circuit fault $\mathrm{St}=6$.


Figure-20. Switch fault in three-phase full bridge T4 Short Circuit fault $\mathrm{St}=1$.
$\mathrm{G}_{3}$ denotes the flaw recognition banner of deficiency sort $\mathrm{F}_{3}$. Gi signifies the deficiency distinguishing proof banner of switch flaw in threestagefull Scaffold. G3_y demonstrates the flaw conclusion banner of the six switches $\mathrm{T}_{1}$ to $\mathrm{T}_{6}$ in three-stage full extension under the issue state of $F_{3}$, where $y=1,2, \ldots, 6$. After the analysis of the issue, shortcoming Insurance measure is taken to release the yield voltage of buck converter keeping in mind the end goal to maintain a strategic distance from the optional flaw. The flaw determination time is appeared as $\mathrm{T}_{\text {fault }} \approx 0.0006 \mathrm{~s}$.
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Figure-21. Switch fault in three-phase full bridge T 4 Short Circuit fault $\mathrm{St}=6$.

Figure-16, Figure-21 demonstrates the recreated aftereffects of deficiency F4. At the point when the lower switch $\mathrm{T}_{4}$ suffers a short out issue, the issue determination forms with the proposed deficiency analysis strategy are appeared in Figure-20, Figure-17. The event of the deficiency condition F4is meant by the banner $G_{40} . \varepsilon_{2}$, $\mathrm{e}_{\text {th2 _s }}$ and $\varepsilon_{4}$ are created to distinguish the short out shortcoming. $\varepsilon_{3}$ is utilized to distinguish the defective switch. $\mathrm{G}_{4}$ denotes the shortcoming recognition banner of flaw sort $\mathrm{F}_{4} . \mathrm{G}_{4} \mathrm{~S}$ signifies the deficiency discovery banner of issue sort $\mathrm{F}_{4}$ when the short out of the complete appendage happens because of the event of flaw $\mathrm{F}_{4} . \mathrm{G}_{4-\mathrm{y}}$ demonstrates the shortcoming analysis banner of the six switches $T_{1}$ to $T_{6}$ under the issue state of $F_{4}$, where $y=1,2$, $\ldots, 6$. It can be learnt that the deficiency determination time of lower switch cut off is under 0.0008 s . After the finding of the issue, shortcoming seclusion measure is taken to detach the startling leading stage with a specific end goal to maintain a strategic distance from the optional deficiency. Similarly, the analysis procedures of upper switch T1short-circuit flaw are appeared in Figures 18, 19 furthermore, the deficiency finding time is under 0.0008 s.

## C. Simulation result of switch fault in BUCK converter by using FUZZY controller



Figure-22. Switch fault in buck converter by considering open circuit fault.


Figure-23. Switch fault in buck converter by considering Short circuit fault.

The simulated results of diagnosis processes of fault $F_{1}$ and $F_{2}$ at the rotor speed of $5000 \mathrm{r} / \mathrm{min}$ are shown in Figure-22and Figure-23. The switch open-circuit fault was inserted through the FPGA by the permanent off signal of the gate driver. Similarly, the switch short-circuit fault was modeled by turning the gate signal permanently on by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance.
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D. Simulation results of switch fault in three phase full bridge by using FUZZY controller


Figure-24. Switch fault in three-phase full bridge T1 open circuit fault.


Figure-25. Switch fault in three-phase full bridge $\mathrm{T}_{4}$ open circuit fault.

The occurrence of the fault conditions $F_{1}$ and $F_{2}$ are denoted by the flags $G_{1 o}$ and $G_{2 o} . \varepsilon_{1}, e_{\text {th1_s }}$ and $e t_{h 1 \_}$are generated to detect the fault. $G_{1}$ and $G_{2}$ denote the fault diagnosis flags of fault $F_{1}$ and $F_{2}$ by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance. In the proposed method, $k_{t f}=5$ is chosen. It can be learnt that with the simulations and analyses. From the simulated, the fault diagnosis time of short-circuit fault and open-circuit fault in buck converter are shown as 0.001 s and 0.003 s respectively by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that

Fuzzy speed controller scheme gives superior performance.


Figure-26. Switch fault in three-phase full bridge $\mathrm{T}_{1}$ short circuit fault $\mathrm{St}=4$.


Figure-27. Switch fault in three-phase full bridge $\mathrm{T}_{1}$ short circuit fault $\mathrm{St}=6$.

The simulation results of the diagnosis process of fault $F_{3}$ and $F_{4}$ are shown in Figure-24 and Figure-25. Figures 26, 27, and Figures 28, 29 shows the simulated diagnosis results of fault $F_{3}$ with the proposed method. The occurrence of the fault condition $F_{3}$ is denoted by the flag $G_{3}$. In the proposed diagnosis method, $\varepsilon_{2}$ and $e_{t h 2 \_}$are generated to detect the open-circuit fault. $\varepsilon_{3}$ is used to identify the faulty switch by the logic shown in Table-2.
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Figure-28. Switch fault in three-phase full bridge T 4 short circuit fault $\mathrm{St}=1$.
$G_{3}$ denotes the fault detection flag of fault type $F_{3}$. $G_{i}$ denotes the fault identification flag of switch fault in three-phase full bridge. $G_{3-y}$ shows the fault diagnosis flag of the six switches $T_{1}$ to $T_{6}$ in three-phase full bridge under the fault condition of $F_{3}$, where $y=1,2, \ldots, 6$. After the diagnosis of the fault, fault protection measure is taken to discharge the output voltage of buck converter in order to avoid the secondary fault. The fault diagnosis time is shown as $T_{\text {faul }} \approx 0.0006 \mathrm{~s}$. Figure-24, Figure- 28 show the simulated results of fault $F_{4}$. When the lower switch $T_{4}$ suffers a short-circuit fault, the fault diagnosis processes with the proposed fault diagnosis method are shown in Figure-20, Figure-17 by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance. The occurrence of the fault condition $F_{4}$ is denoted by the flag $G_{40} . \varepsilon_{2}, e_{\text {th2_s }}$ and $\varepsilon_{4}$ are generated to detect the short-circuit fault. $\varepsilon_{3}$ is used to identify the faulty switch. $G_{4}$ denotes the fault detection flag of fault type $F_{4} . G_{4 s}$ denotes the fault detection flag of fault type $F_{4}$ when the short-circuit of the complete limb happens due to the occurrence of fault $F_{4}$. $G_{4_{-}}$shows the fault diagnosis flag of the six switches $T_{1}$ to $T_{6}$ under the fault condition of $F_{4}$, where $y=1,2, \ldots, 6$.


Figure-29. Switch fault in three-phase full bridge T 4 short circuit fault $\mathrm{St}=6$.

It can be learnt that the fault diagnosis time of lower switch short-circuit fault is less than 0.0008s. After the diagnosis of the fault, fault isolation measure is taken to disconnect the unexpected conducting phase in order to avoid the secondary fault by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance. Similarly, the diagnosis processes of upper switch $T_{1}$ shortcircuit fault are shown in Fig. 25, 26 and also, the fault diagnosis time is less than 0.0008 s by using PI speed controller And Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance.

## 6. CONCLUSIONS

In this paper, a fault detection algorithm for an inverter fed BLDC motor has been proposed for fault diagnosis one of the main components of the fault diagnosis method is voltage observer. The voltage observer is based on the system model of buck converter and three-phase full bridge which used to estimate the buck converter output voltage and motor input voltage respectively. Thus, the residual voltage errors are calculated to detect the fault type. Also, the corresponding fault features are extracted to identify the faulty switch. The open-circuit fault and short-circuit fault in diagnosis has been done for converter fed BLDC motor drive under PI speed controller and Fuzzy speed controller and comparison is also made between two control scheme and it is found that Fuzzy speed controller scheme gives superior performance.

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