Model-based Fault Diagnosis for Voltage Source Inverters

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NANYANG TECHNOLOGICAL UNIVERSITY

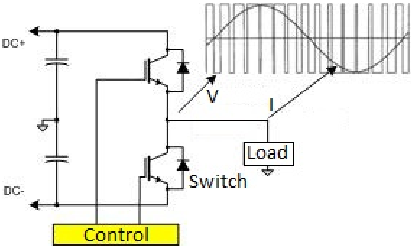
Outline

- Introduction
- Motivation
- Contributions
- Literature Review
- Voltage Space Pattern-based Fault Diagnosis
- Results
- Conclusion

Introduction

Power Electronic Switches:

Basic Structure of Voltage Source Inverters:



Fault Diagnosis

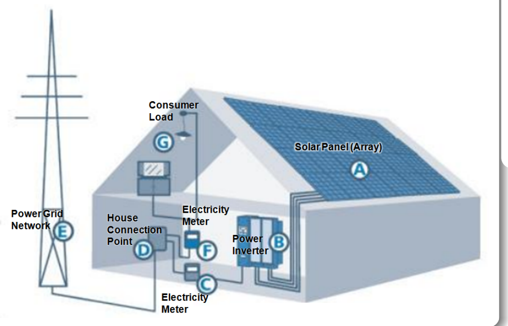
- Fault Detection:
  Is there any short-circuit or open-circuit fault in any of the switches?
- Fault Isolation:
  Where is the location of the faulty switch?

Fault Tolerant Control

- How to protect the system in the presence of a faulty switch?
- How to reconfigure control signals in the faulty situation?

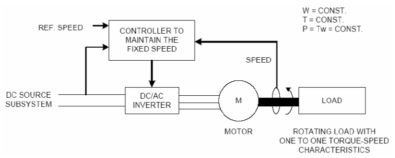
Motivation

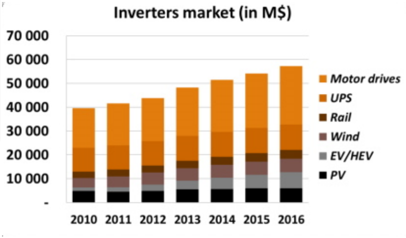
Renewable electrical energy generation systems



Fault diagnosis of power electronic switches is a bottle neck in growing new generation of solar systems based on micro inverters.

AC motor drives





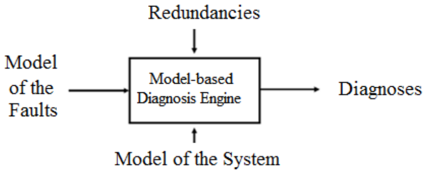
[www.powersystemsdesign.com]

Contributions

- VSP-based FDI for diagnosis of short- and open-circuit switch faults in three-phase voltage source inverters (VSIs).
- Fault diagnosis for multi-level multi-phase inverters.
- Fault tolerant control for multi-level multi-phase inverters
- Design and implementation of an experimental set-up for fault simulation and on-line fault diagnosis
- Validation of the VSP-based FDI method by simulations and experiments
- Validation of the VSP-based FDI method for a PMSM motor-drive application

Literature Review

Model-based FDI

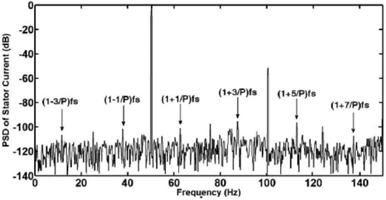


1. Modeling the system:
   To describe the possible ways a certain system can behave in healthy and faulty situations.
2. Feature extraction:
   To determine the fault signatures from the observations.
3. Fault isolation:
   To map the features to the faults.

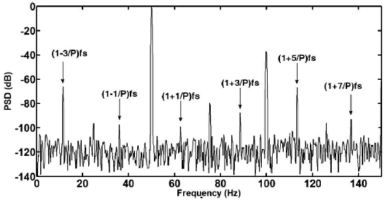
Feature Extraction Techniques

Fourier Transform

Normalised line-current spectra of a motor for healthy condition [1].



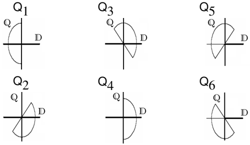
Normalised line-current spectra for a motor with short-circuit turn fault [1].



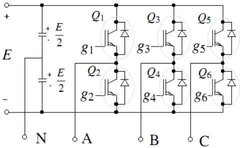
Concordia Transform

$$\begin{bmatrix} i_{\mathbb{D}} \\ i_{\mathbb{Q}} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} i_C \\ i_B \\ i_C \end{bmatrix}$$

The Concordia patterns for an open-circuit fault in a three-phase VSI.



Three-phase VSI



Fault Detection and Isolation Techniques

Fault Detection and Isolation Techniques:

- Limit checking
- Rule-based reasoning
- Neural Networks
- Bayesian Networks
- Qualitative Hybrid Bond Graph

Challenges in Fault Diagnosis for Inverters:

- Hybrid nature of inverters
- Unknown Modes of Operation
- Fast speed of fault propagation
- Limitations in sensor placement

Limitations:

- Expert systems need training; several runs of the system in the healthy and faulty condition is needed
- Access to the internal signals is needed
- The number of required sensors is proportional to the number of switches
- Robustness to the load effects
- Slow fault detection speed ($T_d \approx 20ms = 400 \times T_c$ for $f_c = 20$kHz, f_r =50Hz)

Voltage Space Pattern-based Fault Diagnosis I

Modeling the VSI:

$$\mathbf{v}(t) := \mathbf{e} \cdot \mathbf{D}(t) \tag{1}$$

Pole voltage signals:

$$\mathbf{v}(t) = \begin{bmatrix} \mathrm{v_C}(t) & \mathrm{v_B}(t) & \mathrm{v_A}(t) \end{bmatrix} \tag{2}$$

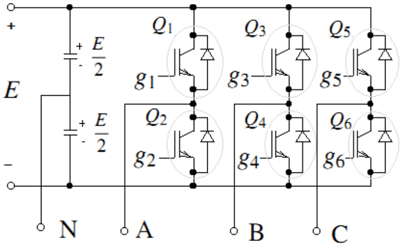
DC source value:

$$\mathbf{e} = \begin{bmatrix} E_N & -E_N \end{bmatrix} \tag{3}$$

Dynamic model of the inverter:

$$\mathbf{D}(t) := \begin{bmatrix} d_1(t) & d_3(t) & d_5(t) \\ d_2(t) & d_4(t) & d_6(t) \end{bmatrix} \tag{4}$$

$$d_i(t) := \begin{cases} 1 & \text{if } \mathrm{Q}_i \text{ is on at time t,} \\ 0 & \text{if } \mathrm{Q}_i \text{ is off at time t.} \end{cases} \tag{5}$$



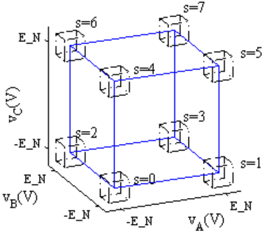
Switching States:

$$s(t) := \mathbf{u} \cdot \mathbf{b}, \tag{6}$$

$$\mathbf{b} := \begin{bmatrix} 4 & 2 & 1 \end{bmatrix}^T, \tag{7}$$

$$\mathbf{u} := \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot \mathbf{D}(t). \tag{8}$$

Voltage Space



Normal switching states

s	$\mathbf{D}_s$	$\mathbf{v}_s$
0	$\begin{bmatrix}0&0&0\\1&1&1\end{bmatrix}$	$[-E_N \quad -E_N \quad -E_N]$
1	$\begin{bmatrix}0&0&1\\1&1&0\end{bmatrix}$	$[-E_N \quad -E_N \quad E_N]$
2	$\begin{bmatrix}0&1&0\\1&0&1\end{bmatrix}$	$[-E_N \quad E_N \quad -E_N]$
3	$\begin{bmatrix}0&1&1\\1&0&0\end{bmatrix}$	$[-E_N \quad E_N \quad E_N]$
4	$\begin{bmatrix}1&0&0\\0&1&1\end{bmatrix}$	$[E_N \quad -E_N \quad -E_N]$
5	$\begin{bmatrix}1&0&1\\0&1&0\end{bmatrix}$	$[E_N \quad -E_N \quad E_N]$
6	$\begin{bmatrix}1&1&0\\0&0&1\end{bmatrix}$	$[E_N \quad E_N \quad -E_N]$
7	$\begin{bmatrix}1&1&1\\0&0&0\end{bmatrix}$	$[E_N \quad E_N \quad E_N]$

Non-equal adjacent switching states:

$$X(t_0) = \langle s(t_0), s(t_1), s(t_2), \ldots, s(t_n), \ldots \rangle, \tag{9}$$

for $n \in \mathbb{N}$, where

$$t_0 > t_1 > t_2 > \cdots > t_n > \ldots \tag{10}$$

and

$$s(t_n) \neq s(t_n^-). \tag{11}$$

Fault Banned Zones

A set of states, $\mathbf{F}_j$, that are not achievable in the presence of a fault in Q$_j$;

$$\mathbf{F}_j := \mathbf{Y}_j^u \cup \mathbf{Y}_j^l - \mathbf{Y}_j^u \cap \mathbf{Y}_j^l. \tag{12}$$

$$\mathbf{Y}_j^u = \{s(t) | d_j(t) = 1, \forall g_i(t) \in \{0,1\}\}, \tag{13}$$

$$\mathbf{Y}_j^l = \{\widetilde{s}(t) | d_j(t) = 1, \forall g_i(t) \in \{0,1\}\}. \tag{14}$$

$$\mathbf{l} := [0\ 1] \cdot \mathbf{D}(t), \tag{15}$$

$$\mathbf{u} + \mathbf{l} = [1\ 1\ 1], \tag{16}$$

thus, from (6),

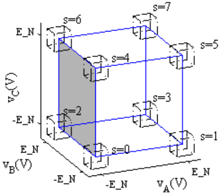
$$\widetilde{s}(t) := ([1\ 1\ 1] - \mathbf{l}) \cdot \mathbf{b}. \tag{17}$$

In the no-fault situation, $\widetilde{s}(t) = s(t)$.

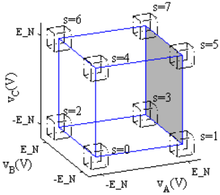
Fault-banned zones of short-circuit faults

Short-circuit fault location (Q$_j$)	Fault-banned zone (F_j)
Q$_1$	$\{0, 2, 4, 6\}$
Q$_2$	$\{1, 3, 5, 7\}$
Q$_3$	$\{0, 1, 4, 5\}$
Q$_4$	$\{2, 3, 6, 7\}$
Q$_5$	$\{0, 1, 2, 3\}$
Q$_6$	$\{4, 5, 6, 7\}$

Fault-banned zone for Q$_1$



Fault-banned zone for Q$_2$



Properties of VSP for SPWM Inverter

PWM signal:

$$p_\varphi(t) := \begin{cases} 1, & r_\varphi(t) \geq c(t) \\ 0, & r_\varphi(t) < c(t) \end{cases} \qquad (18)$$

Reference signal:

$$r_\varphi(t) := A_r sin(2\pi F_r t + \phi_\varphi), \qquad \text{for } \varphi = A, B, C$$

A_r, and F_r are the amplitude and frequency of the reference signal. The Displacement angle $\phi = 0, -\frac{2\pi}{3}, \frac{2\pi}{3}$, for $\varphi = A, B, C$

Carrier signal:

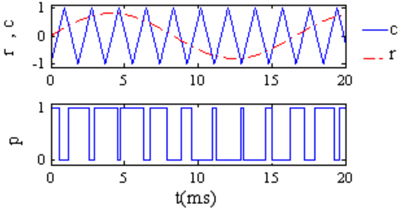
$$c(t) := \begin{cases} 4A_c(F_c t - k - \frac{1}{4}), & \text{if } kT_c \leq t < (k+\frac{1}{2})T_c \\ -4A_c(F_c t - k - \frac{3}{4}), & \text{if } (k+\frac{1}{2})T_c \leq t < (k+1)T_c \end{cases} \qquad k = \lfloor \frac{t}{T_c} \rfloor.$$

Frequency modulation ratio:

$$N := \frac{F_c}{F_r} = \frac{T_r}{T_c} = 3m_1, \qquad m_1 \in \mathbb{N}^+$$

Modulation index:

$$M := \frac{A_r}{A_c} \qquad 0 < M < 1 \qquad (19)$$



1. The switching state s changes whenever one of the PWM signals of a phase leg varies;
2. The state transitions occur at the edges of the cube rather than its diagonals;
3. The state transitions occur at different time instances within one carrier period.
4. For a healthy inverter, six transitions occur within one carrier period.

Procedure of VSP-based FDI

1. Monitoring the pole voltages:

$$\mathbf{v}(t) = [\mathrm{v_C}(t),\ \mathrm{v_B}(t),\ \mathrm{v_A}(t)] \tag{20}$$

2. Extracting switching states:

$$\mathbf{H}_s =: \{\mathbf{h}_s | \forall 1 - \varepsilon_m \leq \varepsilon_\varphi < 1 + \varepsilon_m\} \tag{21}$$

$$\mathbf{h}_s = \mathbf{v}_s \cdot \mathbf{diag}(\varepsilon_\mathrm{C}, \varepsilon_\mathrm{B}, \varepsilon_\mathrm{A}), \tag{22}$$

$$s(t) := \begin{cases} \kappa, & \text{if } \mathbf{v}(t) \in \mathbf{H}_\kappa \\ s(t^-) & \text{otherwise} \end{cases}. \tag{23}$$

3. Comparison of seven non-equal adjacent switching states with the fault-banned sets.

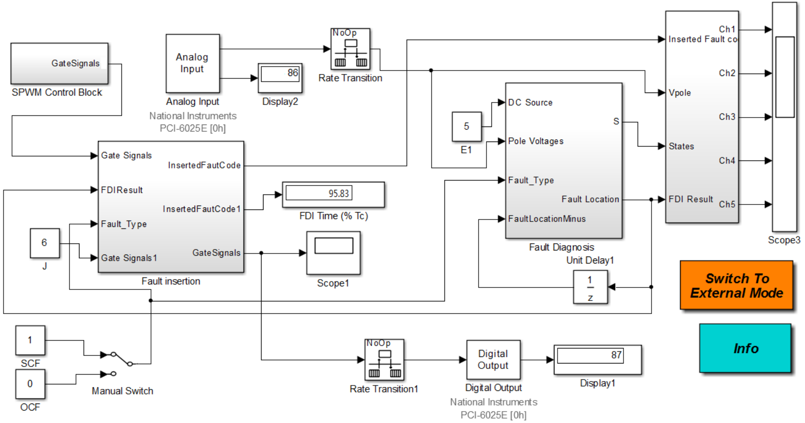
$$W(t_e) = \langle x_{\lambda-2}, x_{\lambda-1}, \ldots, x_{\lambda+3} \rangle \tag{24}$$

- If the phase voltages are monitored for a period of T_c, the value of all phase voltages will definitely change from one level to another one. Therefore, the VSP will not remain inside one face of the cubic pattern for $t_w = t_0 - T_c$.
- If none of the monitored states was a subset of F_j, Q_j is diagnosed as the faulty switch, i.e., if

$$W(t_e) \cap F_j = \emptyset \tag{25}$$

then Q_j is isolated as the faulty switch.

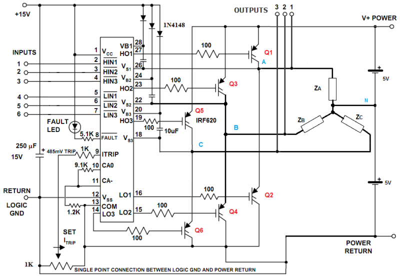
Fault simulator set-up



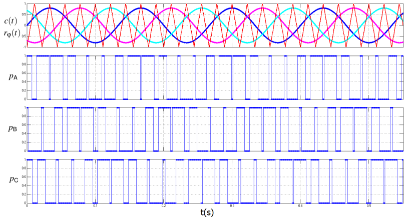
Hardware-In-Loop implementation in MATLAB Simulink using National Instrument Input/Output Card.

Experimental set-up

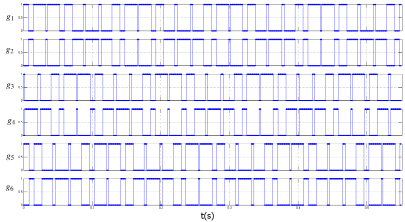
Schematic of the implemented three-phase two-level inverter with IR2130 driver



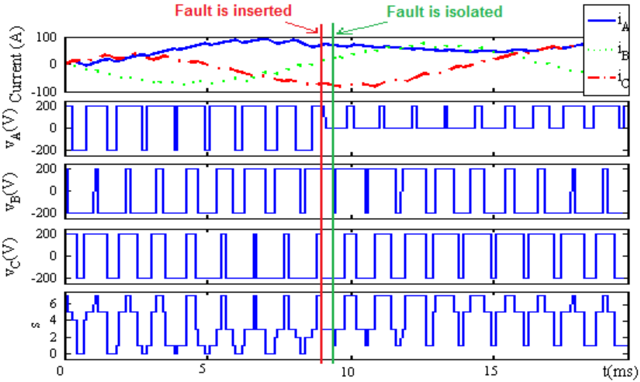
SPWM control signals:

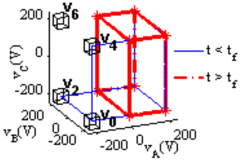


Gate control signals:



Simulation results for diagnosis of a short-circuit fault which occurs at $t_f = 9ms$ in Q_1

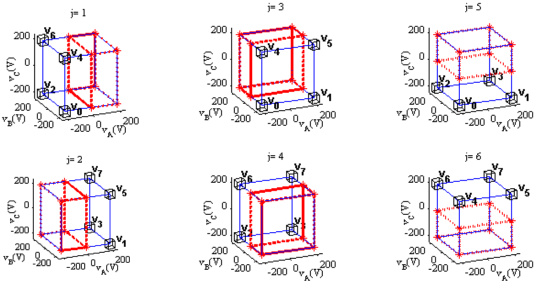


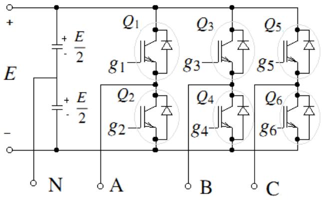


$F_r = 60$Hz
$F_c = 900$Hz
$M = 0.8$
$R = 1\Omega$
$L = 5.6$mH
$E = 400$V

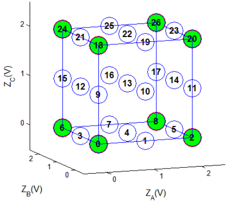
$t_d = 392.5\mu s$=35% of T_c

Fault isolation results for short-circuit faults





Modified approach with 27 states:



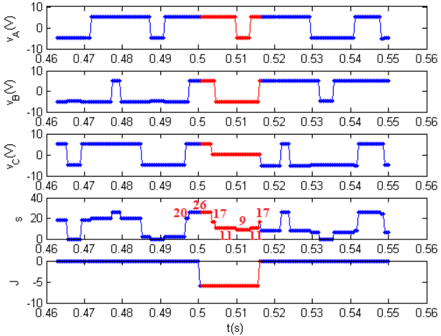
Fault location (Q_j)	Diagnosis time (% Tc)	
	Primary approach	Modified approach
Q_1	70.83	60.42
Q_2	158.33	95.83
Q_3	106.25	95.83
Q_4	131.25	95.83
Q_5	70.83	70.83
Q_6	131.25	95.83
Average FDI time	111.42	85.76

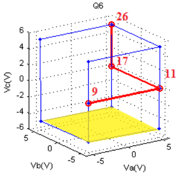
Fault isolation results for open-circuit faults

Open-circuit fault in Q_6

- Q_6 is open-circuited at $t_f = 0.5$s
- The faulty situation is indicate by $v_C \approx 0$
- $W = \{20, 26, 17, 11, 9, 11, 17\}$

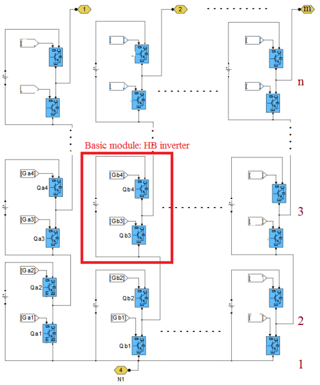
Fault location (Q_j)	Diagnosis time for OCF (% Tc)
Q_1	95.83
Q_2	60.42
Q_3	95.83
Q_4	95.83
Q_5	95.83
Q_6	70.83
Average FDI time	70.83





Fault Diagnosis for Multi-Level Inverters

Schematic of a 3-phase 4-level HB inverter



Modeling the n-level m-phase inverter:

In each phase leg, $N = n - 1$ HB inverter and $q = 2N$ switches exist.
The voltage level of phase φ at time t:

$$L_\varphi(t) = \frac{v_\varphi}{E} = 2\begin{bmatrix}1 & 1 & \cdots & 1\end{bmatrix}_N \cdot \mathbf{G}^\varphi, \tag{26}$$

where

$$\mathbf{G}^\varphi = \begin{bmatrix}G_2^\varphi(t) & G_4^\varphi(t) & \cdots & G_{2N}^\varphi(t)\end{bmatrix}^T. \tag{27}$$

The operating mode of the system at time t:

$$M^\varphi(t) := \mathbf{B}\cdot\mathbf{G}^\varphi, \tag{28}$$

where

$$\mathbf{B} = \begin{bmatrix}2^0 & 2^1 & 2^2 & \cdots & 2^{N-1}\end{bmatrix}_N. \tag{29}$$

Control of the n-level m-phase Inverter I

The control block generates N PWM pulses $p_{\varphi 1}(t), p_{\varphi 2}(t), \cdots, p_{\varphi N}(t)$, by comparing the reference modulating signal, $r_\varphi(t)$, to N triangular carrier waveforms $c_1(t), c_2(t), \cdots, c_N(t)$. For $i = 1, 2, \cdots, N$, and $\varphi = 1, 2, 3, \cdots, m$,

$$p_{\varphi i}(t) := \begin{cases} 1, & r_\varphi(t) \geq c_i(t) \\ 0, & r_\varphi(t) < c_i(t) \end{cases}, \tag{30}$$

where,

$$r_\varphi(t) := A_r sin(2\pi F_r t + \phi_\varphi) \tag{31}$$

The displacement angle between reference and carrier signals, ϕ_φ, is determined by (32),

$$\phi_\varphi = (\varphi - 1)\frac{2\pi}{m}. \tag{32}$$

The carrier signals, $c_i(t)$ for $i = 1, 2, \cdots, N$, is defined as $c_i(t) = \frac{c(t)+(n-2i)}{N}$.

$$c(t) := \begin{cases} 4A_c(F_c t - k - \frac{1}{4}), & \text{if } kT_c \leq t < (k+\frac{1}{2})T_c \\ -4A_c(F_c t - k - \frac{3}{4}), & \text{if } (k+\frac{1}{2})T_c \leq t < (k+1)T_c \end{cases}$$

$$\text{where } k = \lfloor \frac{t}{T_c} \rfloor. \tag{33}$$

Based on the PWM signals, the level of the pole voltage is determined, $H(t) = \mathbf{H}(1, h)$, where

$$h = 1 + \log_2(1 + \sum_{i=1}^{N} 2^{N-i} p_{\varphi i}), \tag{34}$$

The switching modes are selected with two criteria:

1. All of the even voltage levels (normal levels) must be obtained with the selected modes.
2. The selected modes should result in different voltage levels under each fault scenario so that all of the switch faults be isolable.

All of the voltage levels that can be achieved for different modes of the system:

$$\mathbf{L}_{j\,(1\times 2^N)} = \mathbf{T}_{j\,(1\times N)} \cdot (\mathbb{G} + \mathbb{A}_j)_{(N\times 2^N)}, \tag{35}$$

where the columns of $\mathbb{G}$ are the mode numbers in base 2, i.e, and $\mathbb{G}(x, y)$ is the x^{th} digit of y in base 2, and $\mathbb{A}_j(x, y) = \begin{cases} 1 & \text{if } x = k \wedge j = 2k, \\ 0 & \text{Otherwise.} \end{cases}$

$$\mathbf{T}_j = [t_1 \quad t_2 \quad \cdots \quad t_N],$$

$$t_i = \begin{cases} 1 & \text{for } i = k, \\ 2 & \text{otherwise,} \end{cases} \tag{36}$$

$$k = 1 + \lfloor \frac{j-1}{2} \rfloor, \tag{37}$$

and $j \in \{1, 2, 3, \cdots, q\}$ is the location of the faulty switch.

The voltage levels that can be observed in mode M of the system under fault condition Q_j are determined as

$$O(M,j) := \mathbf{W}(1+j, 1+M), \tag{38}$$

where

$$\mathbf{W} = \begin{bmatrix} \mathbf{L}_0 \\ \mathbf{L}_1 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{L}_j \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{L}_q \end{bmatrix}_{(q+1)\times 2^N}, \tag{39}$$

From $\mathbf{W}_{(\mathbf{q+1})\times \mathbf{2^N}}$, proper modes of operation can be chosen such that all of the normal states are achieved in the no-fault situation. There exist V selections where

$$V_{max} = \binom{2^N}{n} = \frac{2^N!}{(2^N-n)!(n!)}. \tag{40}$$

Proper modes of operation are shown in $\mathbf{W}_{v\ (q+1\times n)}$ for $v = 1,2,\cdots,V$, where

$$\forall y,z \in \mathbb{N}, 1 \leq y \leq n, 1 \leq z \leq 2^N | y = 1 + \frac{\mathbf{W}(1,z)}{2} \implies \mathbf{W}_v(x,y) = \mathbf{W}(x,z), \tag{41}$$

for $x = 1,2,\cdots,q+1$.

Several $\mathbf{W}_v$ matrices may be achieved from the above condition. One of them should be chosen by selecting v such that isolability of all of the switch faults is obtained. To achieve this objective, an identification vector ,$\mathbf{D}_v$, is assigned to $\mathbf{W}_v$, i.e.,

$$\mathbf{D}_v(x) = \sum_{h=1}^{n} 2^{\mathbf{W}_v(x,h)}. \tag{42}$$

If the members of $\mathbf{D}_v$ are unique, all of the switch faults are isolable using selected v. In this case, the operating modes are calculated by (43),

$$\mathbf{M}_v = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \end{bmatrix}_{q+1} \cdot \mathbf{W}_v. \tag{43}$$

Fault detection and Isolation for n-level inverters

For $Z_\varphi = 0, 1, 2, \cdots, 2N$,

$$L_\varphi(t) = \begin{cases} Z_\varphi & \text{if} \leq |v_\varphi(t) - (Z_\varphi - N)E| \leq \varepsilon \\ L_\varphi(t - T_s) & \text{Otherwise} \end{cases} . \tag{44}$$

If

$$L_\varphi(t_d) = 2k - 1, \tag{45}$$

a fault in phase φ is detected at $t = t_d$. The isolating modes of the system are applied:

$$M(t_d + w.T_s) = \mathbf{M}_v(1, w), \tag{46}$$

and the system's responses are collected in vector $\mathbf{O}$ for $w = 1, 2, \cdots, n$ observations, where

$$\mathbf{O}(w) = L_\varphi(t_d + w.T_s). \tag{47}$$

Then the collected voltage levels are compared to the rows of $\mathbf{W}_v$. If for $y = 1, 2, \cdots, n$ $\mathbf{O} = \mathbf{W}_v(j+1, y)$, then Q_j of phase φ is diagnosed as the faulty switch, i.e.,

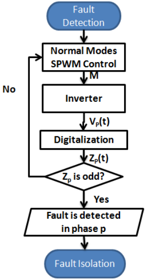
$$\forall y \in \mathbb{N}, 1 < y < n, \mathbf{O} = \mathbf{W}_v(i+1, y) \implies j = i. \tag{48}$$

This procedure needs maximum n observations of the system, thus, diagnosis time is

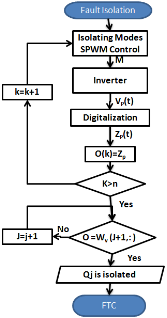
$$t_g = nT_s,$$

that is equal to a few microseconds.

Fault detection procedure for one phase leg:



Fault isolation procedure for one phase leg:



Fault tolerant Control I

1. Protection:

$$\hat{G}^{\varphi}_{2k}(t) = 0, \qquad \text{for } j = 2k-1, \tag{49}$$

$$\hat{G}^{\varphi}_{2k-1}(t) = 0, \qquad \text{for } j = 2k. \tag{50}$$

2. Reducing total harmonic distortion (THD):

$$THD = \frac{\sqrt{\sum\limits_{\alpha=2} I_{\alpha}^{2}}}{I_{rms}}. \tag{51}$$

$$1 \le y \le 2^{N-1}, 0 \le i \le N : \mathbf{W}(j+1,y) = 2i \implies {}_{j}\widehat{\mathbf{M}}(x) = y-1, \tag{52}$$

3. Balancing the faulty Inverter:

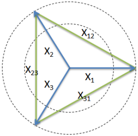
$$|\hat{X}_1(t) - \hat{X}_2(t)| = |\hat{X}_1(t) - \hat{X}_3(t)|, \tag{53}$$

$$|\hat{X}_1(t) - \hat{X}_2(t)| = |\hat{X}_2(t) - \hat{X}_3(t)|, \tag{54}$$

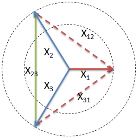
$$|\hat{X}_1(t) - \hat{X}_3(t)| = |\hat{X}_2(t) - \hat{X}_3(t)|. \tag{55}$$

Phasor diagrams of the three-phase 4-level inverter for different situations:

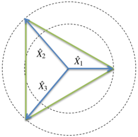
No-fault situation



Fault in phase 1

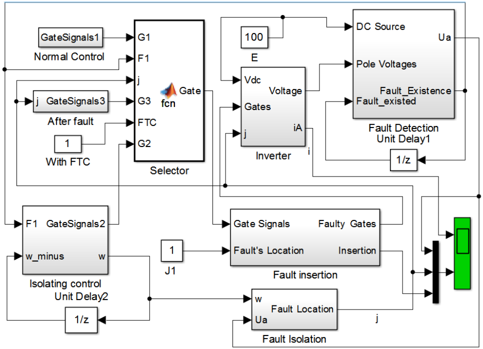


With fault tolerant control

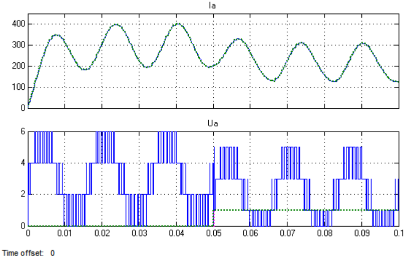


Fault tolerant Control II

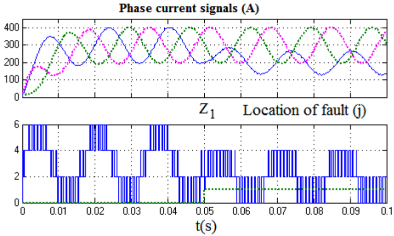
Integrated Fault detection, Fault Isolation, and Fault Tolerant Control for Multi-level Voltage Source Inverter



Fault in Q_1:



With Fault tolerant Control:



Conclusion

- VSP-based FDI method was developed for detection and islation of the short- and open-circuit switch faults in the Voltage source inverters.
- This FDI method is the fastest one in the field
- The FDI method is robust to the load side effects and is aplicable to a wide range of semiconductor switches
- VSP-based FDi was successfully extended to solve the FDI problem of the multi-level inveters.
- The number of required FDI sensors was successfully reduced to only only one sensor per phase leg.
- The FDI method was successfully validated through mathematical proofs, simulations, and online experiments

Recommendations for Further Research

- VSP-based FDI method for vector-space modulated inverters
- Multiple fault detection with VSP
- VSP for diagnosis of incipient faults, aging, and degradation of semiconductor switches and diodes
- VSP for the prognosis of mechaelectronic systems
- Diagnosis of load side faults, such as motor windings
- Integrated fault diagnosis and tolerant motor drive Ics

Thanks For Your Attention!

References

B. Mahdi Ebrahimi and J. Faiz, "Feature extraction for short-circuit fault detection in permanent-magnet synchronous motors using stator-current monitoring," *IEEE Trans. Power Electron.*, vol. 25, pp. 2673–2682, Oct. 2010.