

绝缘栅双极型晶体管故障检测方法:综述与展望*

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摘要: 绝缘栅双极型晶体管广泛应用于航空航天、武器装备、现代工业、交通运输和电力系统等领域。由于其工作环境复杂, IGBT 极易发生异常并导致系统故障, 甚至引发重大的经济损失与人员伤亡。因此, IGBT 的故障检测引起了研究人员的广泛关注和高度重视。但是, 目前针对 IGBT 故障检测技术的系统性综述较稀缺, 阻碍了实际工程人员对其深层次的了解与认知。因此, 该综述从方法的角度对 IGBT 故障检测相关研究成果进行了系统性的回顾: 首先对 IGBT 的基本结构、工作原理以及常见失效机制进行了概述; 其次, 将 IGBT 故障检测技术基于检测方法的差异分为三大类, 并总结了各类方法的优点与不足; 最后, 结合当前技术发展的现状, 对 IGBT 故障检测领域的挑战与展望进行了深层次的剖析。

关键词: 绝缘栅双极型晶体管; 异常检测; 故障诊断; 可靠性

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Fault diagnostic of insulated gate bipolar transistor: Overview and prospect

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Abstract: Insulated gate bipolar transistor (IGBT) is extensively utilized in aerospace, weapon systems, modern industry, transportation, and power systems. Due to the complex environment, IGBTs are highly susceptible to anomalies, leading to system failures and significant economic losses as well as casualties. Consequently, IGBT fault detection has garnered widespread attention and significant focus from researchers. However, systematic reviews of fault detection techniques for IGBTs are scarce, hindering practical engineers' deep understanding and knowledge of this field. Therefore, this review provides a systematic overview of research achievements in IGBT fault detection from a methodological perspective. Firstly, an overview of the basic structure, operation principles, and common failure mechanisms of IGBTs is presented. Secondly, IGBT fault detection technologies are categorized into three major classes based on detection methods, with a summary of the advantages and limitations of each class. Finally, considering the current technological advancements, a deep analysis of challenges and prospects of the field of IGBT fault detection is provided.

Keywords: insulated gate bipolar transistor; anomaly detection; fault diagnosis; reliability

0 引言

绝缘栅双极型晶体管 (insulated gate bipolar transistor, IGBT) 作为至关重要的功率开关装置, 广泛应用于航空航天、武器装备、现代工业、交通运输和电力系统

等领域^[1-3]。但长期在高温高压等苛刻环境下运行, IGBT 极易受到电压浪涌、过电流等因素^[4-6]影响发生异常, 其故障成本约占电力电子系统成本 80%^[7], 因此对于 IGBT 故障检测亟需深入研究以提高系统可靠性和安全性。IGBT 故障通常分为两类: 老化性故障和突发性故障。第一类呈现性能逐渐降低的渐进过程, 主要由长时

料层、DBC 层(上铜层、陶瓷层、下铜层)和铜基板 7 层结构,如图 3 所示^[30]。IGBT 和 FWD 芯片反并联焊接在上铜层,并通过键合引线互连构成功率回路。键合引线通常采用成熟且低成本的铝线键合技术^[31],多条并联提高负载电流容量,降低电气连接阻抗。陶瓷层使上下部分电气绝缘,下铜层焊接在铜基板上将热量传出。最后封装时填充透明硅胶,起到绝缘、防震和均匀导热的作用。近年来,智能功率模块得到广泛关注,通过集成门极驱动、保护电路、传感器和 IGBT 来提高系统性能和可靠性的同时减少设备尺寸^[32]。

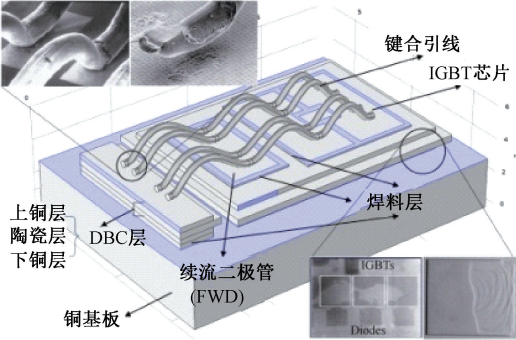


图 3 IGBT 模块结构

Fig. 3 IGBT module structure

2 IGBT 的失效模式

IGBT 失效受多因素综合影响^[29]。如制造工艺引起的结构缺陷,外部环境引起的偶发性失效,长期使用出现的退化现象。失效模式分析如表 1 所示。

表 1 IGBT 失效模式与影响分析

Table 1 FMEA of IGBT

	失效模式	失效机制	芯片级故障	模块级故障
主要失效模式	热失效	热失控	铝金属重构	-
		高温	硅分解	器件失效
	电气失效	电气过应力	开路/短路	结构破坏
		门锁效应	寄生晶体管导通	-
		静电荷放电	栅极击穿	金属化层断裂
	机械应力失效		材料结构变形	焊料疲劳
		热机械疲劳	芯片损坏	键合引线断裂
			-	线路接触不良
次要失效模式		震动冲击	芯片破损	
	环境失效	高湿度环境	金属化腐蚀	电路损毁
		宇宙射线	电化学迁移	性能丧失
		腐蚀性环境	电荷沉积	器件破坏
		半导体杂质	电路板腐蚀	电路损毁
	制造缺陷失效	虚焊	载流子寿命降低	封装裂纹
			-	线路接触不良
表面缺陷		芯片破损	结构破坏	

2.1 主要失效模式

1) 热失效

热循环是 IGBT 失效最重要原因之一^[33],导致结构变形、封装老化和材料失效等热失效。周期性功率损耗的结温循环和温度梯度作用于特性不匹配材料时,收缩膨胀无法同步会形成疲劳应力^[34]。而半导体平均结温会令化学过程热老化^[35],110℃后晶界处塑性变形造成金属化重构^[22],继续升温导致载流子浓度和热失控指数须增加,900℃时硅分解和金属迁移破坏器件阻断能力^[36]。

2) 电气失效

电气失效受电气条件影响,包括静电荷放电和门锁效应失效等^[37]。电参数超过额定范围会导致结构受损,且电压上升较快或波形突变时斜率过大引发的显著位移电流会导致器件失控,形成低阻态通路。而制造运输可能积累大量静电荷导致使用中发生放电,处于高压状态时可能穿透器件材料层,导致栅极击穿等故障发生。

3) 机械应力失效

机械应力失效受应力冲击导致芯片或封装破坏,引发器件失效。疲劳应力超过材料屈服极限时可能会引发封装裂纹、焊点松动和引线断裂等现象,应力冲击会影响元件性能和电压阻断能力,导致电压击穿现象^[38]。

2.2 次要失效模式

1) 环境因素失效

环境因素失效受高湿度、腐蚀性和宇宙射线等影响,包含吸湿膨胀和器件损坏等。高湿度与高压会引发金属化腐蚀、电化学迁移等^[39],导致漏电流增加,逐步丧失阻断能力。而宇宙辐射产生高能原子和离子与半导体中原子碰撞,裂变产物会在半导体中形成沉积电荷^[34]。

2) 制造缺陷失效

制造缺陷失效受制造过程中工艺缺陷影响,如半导体杂质、器件界面缺陷和虚焊等。DBC 层和基板间焊料层是模块最薄弱的附着层^[40],层间受油污影响时内阻增加聚集热量,焊料层会出现裂纹、空洞甚至剥离。

2.3 应用场景下的失效模式

IGBT 的应用领域广泛,如图 4 所示,其工作环境、负载特性和可靠性要求等因素存在显著差异,主要关注的 IGBT 失效模式不尽相同。

航空航天对可靠性要求极高,其中 IGBT 主要用于电力转换和电机驱动系统。超高温、电磁辐射和快速温度变化等导致热失效为主要失效机制^[41],宇宙辐射不断发射的高能粒子极易诱发系统失效^[34],剧烈冲击也易造成机械应力失效。因此对 IGBT 故障检测技术要求严格,包括高可靠性、前兆信息捕获和长寿命预测等。



图 4 IGBT 的应用领域
Fig. 4 The application field of IGBT

武器装备对可靠性和耐久性要求极高,其中 IGBT 主要用于精密控制和能量管理。高功率和高电流等容易引起电气击穿和电迁移等电气失效^[42],剧烈震动极易造成结构损伤。因此需要关注 IGBT 系统高可靠性和即时响应,区别如脉冲负载短时间内大电流等类似故障行为。

现代工业需要不间断长时间工作,其中 IGBT 主要用于变频器和电机驱动。高负载和高频率运行下膨胀收缩和震动冲击等可能造成机械应力失效,特定工业应用高

湿度和腐蚀性环境易使金属腐蚀或材料劣化^[29]。因此故障检测关注高效准确,识别潜在故障避免生产中断^[43]。

交通运输的运行状态多变,IGBT 主要用于电力转换和电机驱动^[44]。较大功率波动和频繁工况变化造成疲劳损伤累积可能导致电气失效^[1],芯片开关长时间产生数百瓦(W)数量级的热量^[45]会导致热失效,外界振动和冲击的影响极易引发器件的机械应力失效。因此对 IGBT 的实时动态故障检测技术有着重要需求,以达到在停止或前进时不间断的进行 IGBT 器件检测^[46]。

电力系统中 IGBT 主要用于电能变换和电网稳定控制。高电压和高功率工作容易导致电气击穿、过热等失效现象,工业电网中电力波动和电磁干扰在过流和过压等保护不及时极易导致电气失效。因此关注长期状态监测和早期故障检测,防止电力供应大规模中断。

3 IGBT 故障检测技术

IGBT 故障检测技术是电力电子领域重要研究方向之一,部分学者对其进行了回顾,中英文综述如表 2 所示。本章在方法层面对 IGBT 的故障检测技术进行总结,分为基于模型、基于信号和基于数据驱动三大类。

表 2 IGBT 故障检测研究综述概况
Table 2 Overview of IGBT detect research

Year	Authors	Content	Topic
2009	Bin Lu et al. [20]	IGBT	Fault diagnostic and protection
2013	Pramod Ghimire et al. [47]	wear-out status of IGBT	Real time physical measurement
2013	Rui Wu et al. [21]	IGBT power electronic converters	Catastrophic failure and fault-tolerant
2014	Hyunseok Oh et al. [48]	IGBT modules	Failure, condition monitoring, and prognostics
2016	Haoze Luo et al. [49]	IGBT gate driving methods	Reliability
2020	Keting Hu et al. [50]	Two-level IGBT-based power converters	Monitoring and fault-tolerant
2021	Ahmed Abuelnaga et al. [29]	IGBT module	Failure modes
2021	Meng Huang et al. [5]	IGBT modules	Detection, estimation, and prediction
2021	David Gonzalez-Jimenez et al. [51]	Electric Drives	Data-driven fault diagnosis
2023	Yongqiang Kang et al. [52]	Welded IGBT Power Modules	Failure Mechanism and Health State Evaluation
2021	李辉等[53]	压接型 IGBT	封装退化监测
2022	牛刚等[1]	车用 IGBT 模块	健康管理
2024	刘泽浩等[54]	模块化多电平变流器 IGBT	开路故障诊断与定位

3.1 基于模型的方法

利用数学模型描述 IGBT 工作机理,模拟其电气特性和热特性进行估计,可以分为解析模型以及物理模型。

1) 解析模型

(1) 状态观测器通过外部变量估计系统状态,对比监测值实现故障检测。文献[55]利用广义梯度下降算法实现自适应参数识别。文献[8]通过产生度量每个故障特征与残差之间相似度信号识别故障相。文献[56]结合条件比较器和低通滤波器确定不同负载条件下阈值。

(2) Luenberger 观测器使用线性方程估计系统状态,文献[57]结合 Luenberger 观测器和开环估计器用于电流和电压传感器。文献[58]结合两个非线性 Luenberger 观测器和方向性评估构建鲁棒性残差进行故障检测。

(3) 混合逻辑动态模型 (mixed logical dynamical, MLD) 用于描述具有离散和连续状态以及混合逻辑规则的动态系统,通常由一组离散、连续状态和切换规则组成。文献[59]结合残差生成检测整流器开关故障。文献[60]利用 MLD 模型估计电网电流诊断开路故障。

(4) 卡尔曼滤波器 (Kalman filter, KF) 是递归滤波

器,融合先验信息和测量信息估计系统状态,适于线性系统且对噪声处理效果好,通过比较测量值和估计值进行故障检测^[61]。文献[10]添加修正方程克服发散问题,改善KF对瞬态过程的鲁棒性且适合非线性系统。

(5)滑模观测器(sliding mode observer, SMO)是动态系统,使用非线性反馈迫使估计输出逼近测量输出。文献[62]结合故障行为知识和SMO解决模型依赖。离散SMO(DSMO)能利用数字控制器并适用较低采样率^[63],用于具有不确定性或扰动的非线性动态模型。文献[9]构造自适应SMO有效抑制抖动并加快收敛。

(6)结构分析(structural analysis, SA)仅考虑模型方程中出现的变量,模型由关联方程和变量的双邻接矩阵来描述,已知数学模型作为先验知识,通过特定的程序化步骤完成目标系统故障诊断^[19]。文献[19]使用SA进行故障预诊断形成关联图。文献[64]根据不同断层条件下解析关系优化至最小结构超定集。

(7)本节案例为基于结构模型的牵引系统脉冲整流器实时故障诊断方法^[64]。首先基于牵引系统SA构建结构模型,根据故障条件下解析关系模型获得最小结构超定集,推导冗余关系并生成序列残差,诊断决策采用累积和算法。实验基于某型牵引系统脉冲整流器搭建硬件在环仿真平台,完成模型实时计算和外界实时信号输出,通过仿真模型与真实控制器实现故障仿真与诊断。

2) 物理模型

(1)有限元仿真(finite element method, FEM)利用有限元分析对系统建模,从物理和化学角度剖析器件失效机理,获取健康和异常状态下物理量分布^[11]。常见仿真软件为COMSOL和ANSYS^[28],通过建立IGBT多物理场有限元仿真模型,可以证明温度梯度的分布^[65]和散热器热阻的减小^[11]能够反映缺陷位置和失效程度。

(2)热模型(thermal model)的构建通常使用Foster和Cauer模型。Cauer模型结合器件结构信息,Foster模型在数学上拟合获得的温度响应。文献[66]考虑芯片和陶瓷层热参数对温度的依赖性模拟散热建立Cauer模型。文献[67]考虑老化条件对热阻和电容参数的影响建立多芯片IGBT模块Foster模型。文献[68]通过线性时不变系统表征动态热行为,利用频域响应在线估算结温。文献[69]表征Foster模型斜率变化来预测热行为。

(3)本节案例为低计算成本的多芯片IGBT模块实时平均结温估算方法^[70]。首先使用平均二维热模型来估算多芯片IGBT模块的虚拟结温,并利用基于最小二乘法的有限元仿真模型进行提取,最后提出基于交错逐周期计算方法的温度估算器,并使用枚举法分析极端工作条件下的估算误差。实验基于T3ster实验平台,测量芯片到冷却液的瞬态热阻抗,获得最大误差来验证模型的准确性,同时搭配故障检测算法,验证结果提高了约65%

的计算效率,节省了63.6%的存储空间。

3.2 基于信号的方法

通过关注系统的输入和输出信号,收集时频特征进行故障检测,可以分为基于时域信号和频域信号的方法。

1) 时域信号

(1)电流检测方法通常基于法拉第感应定律。在大功率IGBT模块中开尔文发射极(e)和功率发射极(E)之间存在寄生电感 L_{ce} ,通过 L_{ce} 两端的感应电压可以提取 di/dt 反馈信号^[71],但是开关尖峰会影响电流测量^[72]。罗哥夫斯基(Rogowski)线圈可以对电流进行无损检测,文献[73]设计了印刷电路板Rogowski线圈来检测IGBT电路中过高 di/dt ,但无法测量低频电流或直流电流且成本较高。文献[72]设计了方形Rogowski线圈,实现更好的定位精度和抗干扰能力。

磁场传感器也可以检测电流信号,最为常见的是霍尔传感器^[36],具有电流隔离功能,能够测量直流、交流和复杂波形电流^[5]。磁阻传感器也是一种很有前途的电流传感器技术^[74],磁阻可分为各向异性磁阻、巨磁电阻和隧道磁阻(tunnel magneto resistance, TMR),文献[75]首次提出环形TMR电流传感器来测量IGBT电流,并将其与保护参考电流进行比较以检测故障。

(2)电流矢量化中公认的3种类型的坐标变换方法是Concordia、Clarke和Park变换。Concordia变换方法将三相电流数据映射为静止参考系上的两相交流等效电流矢量分量^[76];Clarke变换($\alpha\beta$ 变换)将非正交的三相电流方程信息转换为两个正交分量;Park变换(dq 变换)在此基础上以相同的角速度旋转 α 轴和 β 轴,将电流等效到直轴和交轴上。电流矢量法利用3种参考系在稳态下恒定半径的圆,在故障时会发生偏移的特性,通过扇形面积、角度或电流轨迹斜率^[76]可以判断故障或训练网络。Park变换能处理不平衡系统且适用高频信号,也可以同时结合3个参考系^[77]进行判断。

(3)归一化直流电流方法将电流中直流分量归一化为其相应的基波分量,随后在稳定或瞬变状态下使用阈值进行故障检测与定位。Concordia模式可以归一化为平均电流矢量点^[78],将相电流除以Park矢量模数来执行归一化可以改善瞬态误报率^[79],文献[13]通过积分得到3个归一化相电流的平均绝对值作为瞬态条件下检测标准。文献[80]进一步推广,使用归一化直流分量和负载电流附加变量的乘积形成基本诊断变量。

(4)通态压降 V_{ce} 的测量即去饱和检测,是最常见的电压型故障检测方法,也是结温估算和键合线检测最常用的参数检测之一^[4]。其复杂检测电路会干扰系统,文献[74]使用单个电路测量单相逆变器中所有功率半导体的 V_{ce} ,文献[3]使用外部集电极电容器来对其进行监控。文献[4]发现 V_{ce} 在低负载电流下与其结温成线性

关系,高负载电流下与键合线的退化密切相关可以以此监测 IGBT 和 FWD 的结温和键合引线状况。

(5) 栅极电压 V_{ge} 波形首次在文献[25]中用来检测故障,但仅限制在负载故障暂态期间出现的电流峰值,文献[81]给出正常、故障以及负载下故障的 V_{ge} 波形以适应硬开关故障等条件。基于 V_{ge} 行为可以检测 IGBT 开路、短路和键合引线初始故障^[14,82]。同时栅极-集电极面积的变化对 V_{ge} 波形存在影响^[83],通过栅极信号平坦区持续时间可以同时检测 IGBT 开路和短路故障。

(6) 电路中其他电压也会受 IGBT 故障影响,如子模块电容电压^[84]、线电压和相电压^[85]、直流母线电压^[86]等。基于电参数的方法灵敏度高、侵入性小,但需要外加电路来达到精确检测。因此可以利用关断延迟时间^[11]、结温、磁信号^[87]以及特征阻抗参数^[88]等非侵入方式获得的信号来实现故障检测、断口定位微小本征故障定位等。以上多种方法如图5所示。

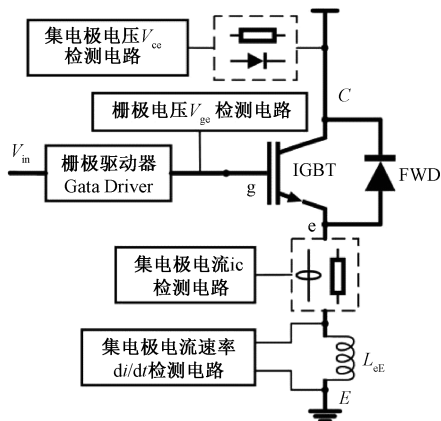


图5 时域信号检测方法

Fig. 5 Time domain signal detection method

(7) 本节案例为基于导通栅极电压过冲的 IGBT 模块键合线故障检测方法^[14]。首先通过理论分析将栅极导通电压过冲作为键合引线脱落指示器;随后其对电流、母线电压和温度依赖性的基准值校准。实验验证基于双脉冲功率测试平台,对比常用的导通状态电压和米勒平台持续时间方法,该方法具有更高分辨率。同时给出实际的测量实施方案,通过分压电路获取 IGBT 的栅极和发射极之间电压,判断 IGBT 故障程度。

2) 频域信号

(1) 快速傅里叶变换(fast Fourier transform, FFT)是最常见的频谱分析方法,可以将信号从时域转换到频域,揭示信号中频率成分和周期性。FFT 通常用作特征提取的方法,用来处理交流波形或磁场信号^[6]等,用作 IGBT 检测故障的指示特征或网络训练参数。

(2) 小波变换(wavelet transform, WT)起源于傅里叶变换,用于分析信号在时间和频率上的局部特征,将具有

短持续时间以及有限能量函数的信号进行转换,同时保持时域和频域的分辨率,使其在处理非平稳信号^[15]和非线性振动方面更为有效。文献[89]使用连续小波变换进行特征提取,作为后续分类模型的输入。

(3) 离散小波变换(discrete wavelet transform, DWT)将信号分解成不同频率成分的逼近系数和细节系数,以离散形式减少计算量和数据存储量。文献[90]对原始信号进行小波分解提取平均值和能量等特征。文献[15]评估9级DWT逼近系数和细节系数的峰度、偏度和RMS值,证明第3级细节系数的RMS参数最有效。

(4) 希尔伯特-黄变换(hilbert-huang transform, HHT)^[16]结合希尔伯特变换和本地特征提取,形成自适应数据处理方法,在处理非线性、非平稳和时变信号时存在优势。其核心步骤经验模态分解是局部处理方法,受初始条件和局部极值点影响,且缺乏专门的噪声处理机制。文献[16]使用自适应噪声的完全经验集成模态分解解决残余噪声以及不同数量模态的存在问题。

3.3 基于数据驱动的方法

通过利用大量的历史数据进行训练,提取潜在特征进行故障检测。可以分为数理统计以及深度学习的方法。

1) 数理统计

(1) 支持向量机(support vector machine, SVM)用于分类和回归,保证局部和全局最优解相同。文献[77]结合递归特征消除减少特征量和计算量。文献[91]提出对称SVM方法检测开路/短路故障。文献[92]使用最小二乘SVM作为故障分类器。文献[93]将梯度信息引入训练数据解决数据较少时回归质量差的问题。

(2) 主成分分析(principal component analysis, PCA)可以捕获变量之间的相关性,并将其表达为一组新的正交变量。然而PCA只在变量线性相关且服从正态分布时有效^[94],于是产生核主成分分析(kernel principal component analysis, KPCA),使用核函数处理非线性关系,文献[94]使用KPCA进行IGBT短路故障检测。

(3) 随机森林算法(random forests theory, RF)是集成学习算法,将由多个独立决策树构成的弱分类器集成为一个强分类器^[95]。文献[96]提出了4种降维核主成分分析法减少测量数量来简化模型。同时,其袋外数据浪费了一定信息,可以用来评估模型性能^[95]或每个决策树诊断性能^[97]来增强检测模型的鲁棒性。

(4) 贝叶斯网络(Bayesian networks, BN)是概率图模型,通过有向无环图表示一组随机变量及其依赖关系,是概率知识表示和推理领域最有用的模型之一。文献[98]结合SVM和贝叶斯学习给出易于接受的概率预测进行分类,在文献[99]中与布谷鸟搜索(cuckoo search, CS)算法相结合,得到了更好的结果。

(5) 极限学习机模型(extreme learning machine, ELM)作为随机学习算法,属于单层前馈神经网络,在训练过程中通过随机初始化、线性回归或其他简单方法计算各层权重,其训练速度非常快,能够解决大量数据的问题。ELM首次由文献[100]引入到电力电子装置故障诊断中,随后被文献[101]用于IGBT的故障诊断中。

(6) 本节使用案例为考虑非平稳影响的基于自动特征提取和随机森林的变流器鲁棒开路故障诊断方法^[97]。首先使用定义的信息分量函数优化最优DWT提取多分辨率时频特性,兼顾独立和交互权重改进ReliefF算法选择重要特征,随后通过袋外数据鲁棒性测试调整决策树权重,最后用粒子群优化确定优化超参数。实验使用维也纳整流器展示非平稳故障过程,用模拟和实测数据进行训练和测试,评估不同负载条件下鲁棒性。离线测试实现99.94%的准确率,在线测试中将模型部署在实际控制系统中进行实时的诊断。

2) 深度学习

(1) 反向传播神经网络(back propagation neural network, BPNN)是最基础的人工神经网络,但是其架构简单,性能不足以支撑高精度诊断需求^[57],通常结合其他模型或硬件加速进行优化。文献[102]基于特征矩阵和独立分量分析联合近似对角化进行故障特征提取以减少输入维度。文献[18]结合遗传算法(genetic algorithm, GA)、蚁群优化和BP算法抵抗噪声干扰。

(2) Elman神经网络(elman neuralnetwork, ENN)是典型的局部回归网络,在前馈神经网络中增加连接层形成局部反馈,具有很强的非线性映射能力,以及任意的复杂因果关系。文献[103]采用改进CS算法优化Elman模型参数,实现诊断精度和速度的最优平衡。

(3) 卷积神经网络(convolutional neuralnetwork, CNN)有着强大的特征提取能力,通过卷积操作捕获局部特征。文献[104]利用深度卷积神经网络(deep convolutional neural network, DCNN)增强复杂特征的学习和表达能力。文献[105]的GA-DCNN使用GA对关键超参数进行优化。文献[106]的CS-CNN使用压缩感知减少训练数据。1D-CNN在处理时间序列时可以减轻计算负担^[107],文献[108]引入自注意力机制对不同分支中1D-CNN多个诊断信号进行降噪融合。

(4) 自动编码器(autoencoder, AE)是由编码器和解码器组成的对称多层神经网络,将输入数据映射到隐藏层并重构。文献[2]提出深度自编码器进行风电机组部件异常检测和故障分析。文献[109]对代价函数进行稀疏约束,实现特征的稀疏表示,得到稀疏自动编码器。深度稀疏自动编码器由层叠的稀疏自动编码器构成,可以设置规则选择深度和隐含神经元数量^[110]。

(5) 深度置信网络(deep belief network, DBN)在观测

信号和标签之间建立了联合概率分布,从而表现出更高的泛化性能。文献[92]的DBN-LSSVM方法选择最佳的输入信号长度提高针对性并减少诊断时间。文献[111]提出基于统计特征的改进深度信念网络,利用直流故障电流的统计特征作为输入。

(6) 循环神经网络(recurrent neural network, RNN)具有循环连接,可以捕捉数据中时间依赖关系,但具有长期依赖问题。长短期记忆网络(long short-term memory, LSTM)是特殊类型的RNN,引入额外的门控单元。文献[112]用128个隐藏层的LSTM进行故障检测。门控循环单元是LSTM的变种,参数更少且计算更快,并引入额外重复链接捕获输入的时间依赖性。

(7) 随机向量函数链神经网络(random vector functional link, RVFL)是随机学习算法,结合了函数链接的单隐层前馈神经网络,原始数据全局信息提高了网络学习和泛化能力。文献[113]使用RVFL提取特征与故障之间的映射关系,调整参数以减轻计算。文献[114]利用RVFL学习历史数据中的故障知识。

(8) 图卷积网络(graph convolutional networks, GCN)通过引入关联图来获取数据之间的关系,从而加快训练速度,提高模型性能,是良好的半监督模型。但该方法严重依赖数据关联图和标签,且使用特征相似度来获得关联图不能保证准确性,文献[19]使用SA综合观测数据以及先验知识来提高模型的诊断精度。

(9) 本节使用案例为异步电机驱动中三相PWM逆变器IGBT和电流传感器故障在线诊断的数据驱动方法^[114]。首先采用FFT算法提取三相电流的故障频谱特征,随后引入ReliefF算法进行关键特征选择,最后用RVFL从历史数据中学习故障特征。实验数据采用CRH3型电力牵引传动系统硬件在环模型与仿真模型相结合的方式采集,共31个运行状态。离线测试中实现98.83%的准确率,在线验证中进行实时硬件在环测试,在22ms内成功识别IGBT和电流传感器故障。

3.4 技术优缺点分析

各类方法都存在一定的优势与局限,本节将从准确性、泛化性、实时性以及难易程度等方面对此进行总结。

基于模型的方法通过数学公式对运行机理进行描述,表征诊断结果与系统参数之间的关系,理论支持很强。物理行为已知时可以充分利用模型信息进行精准估计和故障检测,可对常见故障有效预警。而建立准确模型需要深入理解物理特性和数学方法,尤其面对非线性或多模态等行为和复杂环境,其准确性通常受到影响而导致性能下降。同时求解模型需要大量时间资源,不适合实时性要求较高的场景。其优化方式通常涉及模型设计和阈值选择以提高模型准确性与适应性。

基于信号的方法关注系统输出信号特征并实时监

测,其高响应速度适用于在线检测,只需相应传感器进行信号采集,易于实现与部署。然而信号变换通常只能提供有限故障信息而难以解释故障机制,对复杂或微小故障和恶劣环境无法提供足够的准确性与敏感性。同时泛化性与通用性不足无法适应未知故障、环境变化和不同型号 IGBT,且大量实验导致测试的不可行性、实验的高成本和复杂性问题。其优化方式通常基于电路复杂度、无损检测、噪声敏感度等方面进行改进,以减轻电路干扰瞬态误报率问题,增加检测的鲁棒性。

基于数据驱动的方法利用大量历史数据进行统计分析或深度学习挖掘潜在故障模式,对于不同类型故障具有较高识别能力,适用范围广泛的同时能够学习随时间变化的系统行为,在准确性、实时性和泛化性方面表现良好。而模型的训练与验证需要庞大且高质量数据集,且无法提供直观物理故障机制解释,诊断结果缺乏可解释性。其优化方式通常从数据维度、特征提取、模型参数以及梯度信息的角度出发,降低计算时间的同时充分学习数据特征,提高检测速率与诊断精度。

综上所述,不同应用场景下需综合考虑实际需求、系统特点和可用资源等因素选择合适的故障检测方法。

4 IGBT 故障检测的挑战与展望

IGBT 故障检测为实际的工程应用创造了巨大贡献,但仍然存在一些难题尚未充分解决,包含以下几个方面:

1) 耦合复杂问题。IGBT 失效在微观尺度涉及电子传输、载流子复合、热传导等多个复杂物理过程,且与宏观尺度存在相互耦合,导致模型构建存在难度。如何有效捕捉和处理并整合复杂耦合效应是一大挑战。

2) 模型依赖问题。3 大方法对系统结构有不同程度依赖性,难以适应未知或变化的系统,而实际存在拓扑结构多样、电路参数变化以及控制策略复杂等情况。如何根据实际进行模型快速更新是亟待解决的难题。

3) 非平稳性问题。长期运行中材料特性、器件性能和运行状态等会缓慢变化导致非平稳过程,而检测模型通常是静态的,后续变化会影响准确率和可靠性。如何确保模型动态适配整个运行周期是一大挑战。

4) 经验融合问题。实际过程不仅存在大量电压、电流等数据信息,还存在大量电路拓扑结构、器件运行机理等非数据信息。如何充分融合两种类型信息,将经验知识与数据分析相结合,是故障检测的一项挑战。

基于上述问题的讨论以及研究成果的分析,未来可能成为热点的研究方向如下:

1) 高精度建模与仿真。目前 IGBT 有限元仿真模型基于电-热-力耦合分析,而忽略磁场等其他物理场影响。实现丰富的多物理场耦合,建立高精度物理模型以全面

揭示 IGBT 工作失效机理,是未来的发展方向之一。

2) 跨尺度模拟与分析。针对 IGBT 运行机理的建模应考虑多尺度耦合效应,将原子级、晶粒级、器件级、系统级等不同尺度模拟方法进行有机整合,以揭示微观机理与宏观表象的关联性,提供优化方向与策略。

3) 多模态与多源信息融合。提取多种类信息进行融合能够有效提高检测精度,如多类型数据(电磁与温度等)与多尺度信息(时间与空间等)等,可以通过多传感器信号综合分析,或采用图结构融合拓扑信息。

4) 动态与适应性检测。故障检测方法应具备适应性与动态性,可以考虑适应性算法或增量学习等实现不断变工况下的故障检测,使得算法具备更强的泛化能力,适用于多种工作条件以及不断退化的元器件。

5) 一体化采集与检测。在系统中集成高精度分布式采集、轻量级数据分析和多重保护机制,实现重要参数快速监测、运行状态及时检测和运行电路实时控制,确保在高频率、大规模数据处理场景下安全高效运行。

5 总 结

该综述针对 IGBT 故障机理、检测方法和未来展望 3 个方面,系统总结 IGBT 故障检测技术的发展现状。首先在器件方面介绍其基本结构与工作原理,结合模块特征分析失效机理;其次将故障检测分为基于模型、信号和数据驱动 3 大类,阐述其原理、发展与优缺点;最后基于研究现状分析 IGBT 故障检测的现存挑战与潜在趋势。旨在为工程应用与学术研究提供一定参考。

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