国际电气工程先进技术译丛

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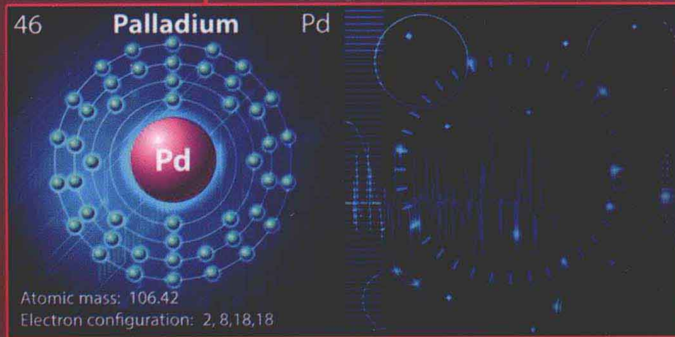
智能电网中的传导电磁干扰

Conducted Electromagnetic Interference (EMI) in Smart Grids

（波兰）Robert Smolenski 著

崔强 吕英华 叶畅 译



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本书详细地讲述了智能电网中的传导电磁干扰（Electromagnetic Interference，EMI）问题。作者通过很多实验和仿真，使读者更进一步地认识和理解智能电网中传导电磁干扰的形成机理、干扰源、测量方法、测量法规以及这些干扰源的抑制技术，并将其用于自己的设计实践。全书共分 7 章，内容包括智能电网中的电力电子接口，传导电磁干扰的标准化测量，智能电网中的传导电磁干扰问题，智能电网中 EMI 特性的改变，电力电子接口中干扰源的补偿，智能电网中的 EMI 测量程序以及对本书的总结。

本书可供智能电网中使用的电力电子产品的设计人员、电磁兼容工程师和系统集成的设计人员使用，也可作为高等学校工科电力和电子信息类专业研究生的参考教材。

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译者序

智能电网是电网技术发展的必然趋势。近年来，通信、计算机、自动化等技术在电网中得到广泛深入的应用，并与传统电力技术有机融合，极大地提升了电网的智能化水平。传感器技术与信息技术在电网中的应用，为系统状态分析和辅助决策提供了技术支持，使电网自愈成为可能。调度技术、自动化技术和柔性输电技术的成熟发展，为可再生能源和分布式电源的开发利用提供了基本保障。通信网络的完善和用户信息采集技术的推广应用，促进了电网与用户的双向互动。随着各种新技术的进一步发展和应用并与物理电网高度集成，智能电网应运而生。

智能电网中要使用大量的设备实现上述的业务，这些设备中使用的电力电子变换器、有源整流器、四象限变频器和DC/DC变换器，会产生严重的传导电磁干扰问题。因此，智能电网中的电磁兼容（EMC）问题是目前国际上学界研究的热点。由于其为全新的发展技术，这些EMC问题也是产品设计工程师急于要解决的问题。

Robert Smolenski教授编著的《Conducted Electromagnetic Interference (EMI) in Smart Grids》一书，详细地讲述了智能电网中的传导电磁干扰问题。作者通过很多实验和仿真，使读者更进一步地认识和理解智能电网中传导电磁干扰的形成机理、干扰源、测量方法、测量法规以及这些干扰源的抑制技术，并将其用于自己的设计实践。全书共分7章，内容包括智能电网中的电力电子接口，传导电磁干扰的标准化测量，智能电网中的传导电磁干扰问题，智能电网中EMI特性的改变，电力电子接口中干扰源的补偿，智能电网中的EMI测量程序以及对本书的总结。

本书可供智能电网中使用的电力电子产品的设计人员、电磁兼容工程师和系统集成设计人员使用，也可作为高等学校工科电力和电子信息类专业研究生的参考教材。

参加本书翻译的有崔强博士、吕英华教授和叶畅工程师。崔强和吕英华共同完成了全部翻译稿的统稿和审校工作。在本书翻译的过程中，得到了本书的著者Robert Smolenski教授的帮助和支持，得到了机械工业出版社朱林编辑提出的许多修改建议，译者在此表示诚挚的感谢。此外，译者还要特别感谢机械工业出版社对我们的厚爱和信任，把本书交予我们翻译。由于译者水平有限，翻译时间紧，书中的不妥之处在所难免，敬请广大读者批评指正。

译　者

致　　谢

感谢电气工程学院同事们的帮助以及对本书的技术性建议。

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引　　言

由于电能易于远距离传输和易于转换为其他能量形式，因此，它已成为最方便和最有用的能量形式。但电能最大的缺点是不易存储，发电时就必须使用。要存储大量的电能，通常必须转换为其他能量形式，这将显著地降低电能的利用效率。电力系统通常被认为是迄今为止所建造的最大和最复杂的发电机，它能够不间断地向用户传输符合质量参数要求的电能。

传统集中供电式的电力传输系统——利用基于矿物燃料的化石类能源，当前正在转变成为一个现代的和分散的系统，在此系统中可再生能源正在起着今后也必将起着日益重要的作用。然而，可再生能源经常会由于能量流动方向上的动态稳定性、电压分布和电压变化等性能的下降而在电力传输系统中产生骚扰。系统变化产生的这些有害影响可通过电网技术以及能源和电网资源的有效柔性管理的发展而得到解决。上述提到的第二个要求构成了所谓的智能电网（Smart Grid，SG）的基本特点[9,11,33,35,41,42,45,51,57,64,104,106]。智能电网的原理假设消费者、供应商和生产者之间是互连的。这种注重实现终端用户要求的交互式网络的特征是高可靠性和控制的灵活性[40,48,54,74,79,82,84,96,99,103,105,115,86]。

当前，智能电网并没有严格规定的定义，此外，电力系统领域中的不同权威给出的智能电网概念也显著不同。智能电网的概念可参考以下这些机构给出的定义：European Union Smart，the US Department of Energy，UK Super-Gen，Electricite de France（Power-Strada），IBM，EPRI（IntelliGrid），General Electric，Hydro Quebec Automation[30,38,44,45,52,88,109]等。

根据研究文献，智能电网被规定为具有以下特殊性和特征的电力系统。

1）电网应允许可再生能源产生的大量能量的接入。为了实现假设的可再生能源高的占有水平，需要使用高级计量和控制技术（电网的自动化能够实现增加可靠性的孤岛运行）、能量存储装置和需求管理技术，例如，积极需求响应（Active Demand Response，ADR）[6,16,18,19,25,31,43,54,55,67,68,72,73,75,82,112]。

2）这种系统的典型特点是高质量的电能，同时消除了高次谐波、电压跌落、电压暂降、电压中断和相电压的不对称。系统中要求使用由系统运营商控制的电力电子装置，它们被安装在终端用户的电源中或者用于保护工业用户的单个敏感装置。此外，分布式能源的电力电子接口（Power Electronic Interfaces，PEI）作为功率调节器，能够提高电源质量（Power Quality， PQ)[3-5,7,11-14,27,36,37,58,60,66,69,72,97,98,106,107]。

3）终端用户在智能电网中起着积极的作用，它们既是电能的消费者又是电能的生产者——即所谓的“生产消费者”（智能楼宇，智能城市）。电能生产和消费过程的管理，能够改善电压分布、电能生产和需求的本地平衡以及增加电能的分配效率[8,16,43,59,83,100,106,107,113]。

4）智能电网必须准备面对新的挑战，例如，电动车辆市场的发展。电网应能够让电动车辆作为电网的有源元件使用车辆的充电设施。大量的车辆电池被认为是容量非常大的能量存储装置，它们能增加电源的可靠性。装有双向电力电子变换器的电动车辆充电终端允许双向的能量流动，因此可以利用它们作为本地功率调节器（V2G 即车辆到电网技术）[5,13,14-16,29,31,32,34,49,71,81,83,92,100,110,114,121]。

通过利用智能电网技术，能够得到的主要优点有：

1）减少了二氧化碳的排放；

2）增加了分布式可再生发电的参与；

3）尽可能地减小过载情况时分布式发电的脱网过程；

4）调节峰值负载（减小最大能量需求）；

5）提高电源质量；

6）改善电压分布；

7）输电系统运营商（Transmission System Operator，TSO）和配电系统运营商（Distribution System Operator，DSO）之间的协作；

8）电力系统设施的高效管理和利用；

9）电力系统的协调恢复；

10）配电系统可以利用电动车辆的充电设施；

11）减小了输电损耗；

12）其他优点：电力系统设施更有效的管理和利用，能够灵活地适应电能市场的变化。

智能电网中这些优点的技术实现基于现代测量（智能计量）、控制系统以及电力电子变换器的应用。电力电子变换器能够改变电压电平和频率、相移、逆变和整流，提供智能电网中成功应用的不同业务[2,4,7,12,17,20,26,56,60,64,71,93,101,118]。

电力电子变换器在电力系统中执行规定的功能。一方面，它们与供电网相连，而另一方面，它们与负载或另一个供电网相连。这样的系统通常不是永久性的配置，能量转换方法可能根据经济和技术条件进行变化。

在含有电力电子变换器的系统中，根据信号的功率和频率，能量的实现过程会显著不同。作为有意过程（电功率的转换和控制过程）产生的有害影

响的电磁干扰（EMI），会出现在宽的频率范围内——从电源频率的谐波和间谐波一直到微处理器时钟的高次谐波。开关频率的增加会将主能量转换过程产生的高能量干扰转移到传导电磁干扰的频率范围（9kHz~30MHz）。

在使用的大多数电力电子器件中，功率晶体管通常作为快速的无触点开关。对于要实现的控制算法，开关单元的性能应接近理想开关，确保获得最小的开关损耗。另一方面，晶体管开关动作电压极快的上升和下降时间，其产生的大的 $\mathrm{d}u/\mathrm{d}t$ 会产生寄生耦合，从而导致高电平 EMI 电流的流动[23,24,28,50,61,63,70,76-78,89-91,102,111,119]。这就是为什么随着全控快速半导体电力装置的推广应用，在电力电子系统中出现了大量严重干扰发射问题的原因。目前，在电力电子变换器中使用的主要电力开关为绝缘栅双极型晶体管（IGBT），在频率较高的系统中使用的是金属氧化物半导体场效应晶体管（MOSFET）。参考文献［22，53，62，94，95］非常详细地研究了伴随晶体管开关的物理过程。进行这样分析的目的是优化控制电路的设计，减小开关损耗。从电磁兼容的角度，尤为重要的是理解在典型配置的功率电路中开关的动态特性，以及区分影响输出波形的形状和变化率的因素。

智能电网技术的广泛使用，给确保这些特定系统的电磁兼容性（EMC）带来了新的挑战。给电力系统提供智能电网业务时，通常要求使用敏感的智能计量设备[1,10,15,21,39,46-48,59,65,73,79,80,84,85,87,96,103,105,108,112,114,116,117,120]，它们会与产生高电平 EMI 的电力电子变换器相连。因此，这种集成和复杂的系统必须满足电源质量，电源端以及负载端传导电磁发射的有关法规要求，同时必须确保使用了控制和计量系统的电力电子变换器内部的 EMC。此外，由于大量电力电子变换器和控制装置典型地位于附近的系统中，为了确保智能电网系统的正确和可靠运行，必须考虑 EMC 标准中没有规定的但和 EMC 有关的特定问题。这些特定问题包括一组电力电子变换器产生的干扰源的叠加，变换器输入端和输出端的干扰流过远端的电路，变换器产生的干扰影响控制信号的传输等，为了确保系统的可靠性，对这些特定问题进行专门深入的分析很有必要。满足专门制定的 EMC 要求似乎是调节智能电网系统正确设计的关键和必要因素。

目的

在上述讨论的基础上，我们可以表明，本书的主要目的是讲述伴随智能电网技术的应用而出现的新的特殊传导 EMI，同时推荐了能够确保智能电网系统兼容性和可靠性的有效方法。

目的是描述与应用智能电网技术时产生的有害影响相关的传导 EMI，以及给出了有效专用的 EMI 滤波方法。为了实现这个目的，本书的第一部分讲述了 EMC 分析，从智能电网系统可靠性的角度来说，这些分析很重要，当

今与之相关的参考文献中并没有讲述这些内容，同时国际传导 EMI 标准也未予以包括。除了上述内容，还讲述了智能电网中普遍使用的单个电力电子变换器产生的 EMI 的测量结果和分析，干扰进入低压线和中压线的实验评估，一组电力电子变换器产生的叠加干扰的数学计算方法和实验结果，具有确定和随机调制的电力电子变换器产生的 EMI 对控制信号传输的影响，以及在智能电网的符合性评估中，EMC 标准化测量程序的局限性。

在第一部分讲述的背景信息的基础上，第二部分给出了特别建立的，用于减小 EMI 的专用方法。该部分讲述了典型的减小 EMI 的方法，这些方法通过改变 EMI 电流的路径阻抗特性，安装无源 EMI 滤波器和使用所谓的好的工程实践方法来减小 EMI。该部分同时讲述了通常忽略的这些技术对系统内部兼容性不同方面的有害影响。特别推荐应用于智能电网系统的更复杂方法，是采用有源或无源串联补偿电压干扰源，这种方法既能避免干扰流过更多的电路，又能避免干扰的叠加。

最后，本书的第三部分推荐采用 EMC 标准和使用时域测量用于智能电网兼容性的评估，同时给出了一些将来研究的可能方向。

当详细分析时，本书共分 7 章。

本书首先概述了智能电网的主要内容，智能电网系统中出现的传导 EMI 以及本书的整体特点。

第 1 章讲述了通过应用智能电网技术能够实现的系统业务，以及实现所规定的业务的装置其个体技术解决的建议，同时讲述了电力电子变换器作为接口能够从技术上实现系统控制任务的特殊作用。作为脉冲式电能变换产生的有害影响，在含有电力电子变换器的系统中会观察到高电平的传导 EMI。智能电网系统中典型使用的单个变换器被认为是 EMI 源。

第 2 章讲述了在标准化的电磁发射测量中使用的测量技术。从 EMC 分析的角度来说，很有必要理解使用装有精确检波器的超外差 EMI 接收机进行电磁发射测量的特殊性，尤其是在传导发射的频率范围。本章同时讲述了与智能电网系统密切相关的标准规范以及此领域内缺少的法规。

第 3 章主要讲述了与传导 EMI 有关的问题，尤其是与智能电网系统相关的。内容包括 EMI 电流路径中典型耦合阻抗特性的测量结果，电力电子接口产生的干扰的实验结果，低压网和中压网中干扰的流动，具有确定和随机调制的电力电子变换器产生的电磁干扰叠加的数学分析以及测量结果，以及智能电网中不满足电磁兼容性时产生的风险。

第 4 章讲述了通过改变 EMI 电流路径的阻抗频率特性以改变 EMI 频谱的方法。利用不同的滤波结构以及使用好的工程实践，能够有意地改变智能电网系统中的阻抗。

第5章讲述了补偿干扰电压的方法，该干扰电压产生了流动的干扰电流。推荐的这种补偿方法为最佳方法，既能避免以上提到的EMI电流流过多个电路，又能避免一组变换器产生的干扰的叠加。本章还讲述了在典型两电平电压源逆变器的输出端和多电平逆变器中干扰电压的有源和无源补偿方法，在这些情况中更易进行补偿。在原用于逆变器输入结构的补偿原理的基础上，研制出了新的专门用于以下智能电网电力电子接口的无源EMI电压补偿器：有源整流器、四象限变频器和DC/DC变换器。

考虑到实验结果和理论分析，第6章讲述了目前使用的测量程序的局限性，给出了修改频域的测量程序以及通过引入时域测量扩展研究范围的建议。

第7章总结了得到的结果并给出了下一步研究工作的建议。

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