Journal of Electrical Engineering 电气工程, 2014, 2, 31-37
Published Online June 2014 in Hans. http://www.hanspub.org/journal/jee
http://dx.doi.org/10.12677/jee.2014.22005

Summary on Optimal Dispatch of Virtual Power Plant

Qizhi Feng, Jie Yu, Bin Shi

School of Electrical Engineering, Southeast University, Nanjing
Email: 101011274@seu.edu.cn

Received: Apr. 18th, 2014; revised: Apr. 28th, 2014; accepted: May 12th, 2014

Abstract

Virtual Power Plant integrated larger numbers of distributed generations, energy storage devices and loads into a controllable independent power plant by advanced communication technologies and control strategies. It can solve the control and dispatch problems of distributed generations connecting to network effectively by a series of large-scale means. In this paper, we made a comprehensive review on virtual power plant from the aspects of information exchange architectures, operation and management structures, ancillary services and optimal scheduling respectively as well as explored the energy management optimization scheduling problems of virtual power plant deeply. For the optimal scheduling problems, we analyzed in detail mainly from three aspects of optimization goals, scheduling periods and the uncertainties in virtual power plant. Finally, some suggestions are given for further studies of virtual power plant on organizational structure, scheduling management, operational control and so on, so as to form a practical theoretical framework.

Keywords

Virtual Power Plant, Distributed Generations, Optimal Dispatch

虚拟电厂优化调度综述

冯其芝，喻　洁，时　斌

东南大学电气工程学院，南京
Email: 101011274@seu.edu.cn

收稿日期：2014年4月18日；修回日期：2014年4月28日；录用日期：2014年5月12日

摘　要

虚拟电厂将多个分布式电源、储能装置和负荷等分布式单元通过先进的通信技术和控制策略有效集成为可控的独立发电厂，以规模化的手段有效解决分布式电源并网的控制调度问题。本文分别从信息交互架构、运行管理架构、辅助服务、优化调度等方面对虚拟电厂进行了全面综述并深入探究了虚拟电厂能量管理优化调度问题。对虚拟电厂优化调度问题主要从优化模型中的优化目标、调度周期以及虚拟电厂内不确定性因素的处理3个方面进行了详细分析。文章最后还指出对虚拟电厂组织构成、调度管理、运行控制等各方面的研究仍待深入探索，形成可实用化的理论框架。

关键词

虚拟电厂，分布式电源，优化调度

1. 引言

世界能源消费的持续增长以及环境污染的不断加重促进了分布式电源的广泛应用。但随着分布式电源大规模接入电网，大量地域分散、类型各异的分布式电源如何运行管理，成为绿色能源推广应用所面临的难题。虚拟电厂(VPP)为分布式电源运行管理提供了现实可行的解决方案，可充分发挥分布式电源效益，提高用户供电可靠性。

当前，虚拟电厂仍处于理论研究和前期试点的发展阶段，对虚拟电厂的定义尚未统一。文献[1]提出虚拟电厂为一系列不同技术的融合，可有多种运行模式，可连接在配电网的不同节点处。文献[2]定义虚拟电厂是一个有不同类型分布式电源的集合，这些分布式电源可分散在中压配电网不同节点处。文献[3]则指出虚拟电厂是一个多技术和多站点的假设实体。一般认为虚拟电厂是多个分布式电源，可控负荷及储能装置的集合。虚拟电厂可分为商业型虚拟电厂(CVPP)和技术型虚拟电厂(TVPP)[4]，技术型虚拟电厂是从系统管理角度考虑的虚拟电厂，提供的服务和功能包括为配电系统管理者(DSO)提供系统管理、为输电系统管理者(TSO)提供系统平衡和辅助服务；商业型虚拟电厂是从商业收益角度考虑的虚拟电厂，基本功能是基于用户需求、负荷预测和发电潜力预测，制定最优发电计划，并参与市场竞标[5]。

虚拟电厂开展仅有十余年，其早期项目主要集中于欧洲和美国。数据显示[6]，截至 2009 年底，全球虚拟电厂总容量为 19.4 GW，其中欧洲占 51%，美国占 44%；截至 2011 年底，全球虚拟电厂总容量增至 55.6 GW。欧洲的虚拟电厂以实现分布式电源可靠并网和电力市场运营为主要目标，其内的分布式电源占可再生能源(DER)的主要成分；而美国的虚拟电厂则主要基于需求响应计划发展而来，兼顾考虑可再生能源的利用，其虚拟电厂内可能不含分布式电源，可控负荷占据 DER 的主要成分。当前，虚拟电厂在中国还是一个崭新的概念，但虚拟电厂的特点符合中国电力发展的需求与方向，在中国有着广阔的应用前景。当前国外典型的虚拟电厂项目主要集中于欧洲[7]。FENIX 是一个整合各种潜在供能资源的灵活电网项目[8]。该试点项目是由欧盟 8 个国家的 19 个研究机构和组织联合开展的，旨在将 DER 整合入大型虚拟电厂并对其进行分级管理，以优化 DER 在电力系统中的运作。荷兰 PM VPP 以电力匹配器(power matcher, PM)作为多智能代理，每个 DER 设备是一个代理，该代理以不同优化方式进行设备的相关操作，并由集中代理来聚合各 DER 设备代理[9]。德国 Pro VPP 项目将小型分布式发电厂联网，形成可从中央控制站统一运营的虚拟电厂，为电力公司创造新的电力供应源[10]。

2. 虚拟电厂研究现状

当前对虚拟电厂的研究主要集中于信息交互架构[11]-[13]，运行管理架构[14] [15]、辅助服务[16]-[21]以及虚拟电厂能量管理优化调度等方面。

在信息交互架构方面，文献[11]建立了基于 IEC 61850 标准的虚拟电厂通用信息模型，提出基于驱动的多厂商环境下的可扩展信息服务架构；文献[12]建立了虚拟电厂的 CIM 模型，用一系列 UML 图表示虚拟电厂各部分管理间的联系，通过建立统一的公共平台可方便不同运营商间的数据交换，提升不同领域间的通信便利性；文献[13]对含电动汽车的虚拟电厂提出了一种基于 V2G 集成到 VPP 中的结构框架并给出了该结构下的通信需求与通信协议。在运行管理架构方面，文献[14]构建了虚拟电厂和微电网的分层控制结构，并进行了对比。文献[15]基于系统工程方法形成了一个有一定规模的模块化层次化的虚拟电厂。

辅助服务[16]是指可保证电力系统安全、可靠、稳定运行的服务，可包括频率控制、电压控制、阻塞管理、峰值削减消费、市场驱动控制、黑启动等服务。对此文献[17]提出了一种大规模虚拟电厂频率控制策略，文章引入分布式协调算法研究小型负荷与发电单元参与系统频率稳定性研究的适用性；文献[18]基于 FENIX 项目南部方案提出了一种虚拟电厂协调电压控制方法，该方案中的 DSO 可根据当地配电网 SCADA 参数和网络拓扑结构等信息，进行状态估计，确定分布式电源与输电系统的连接点潮流，从而在节点电压偏移时进行电压无功控制，以维持节点电压。文献[19]研究了含多个小型水力发电单元的虚拟电厂电压控制策略。文献[20] [21]还介绍了虚拟电厂有功－无功(P-Q)控制策略。

3. 虚拟电厂调度

当前虚拟电厂优化调度主要为集中式调度。集中控制下的虚拟电厂，要求电厂对涉及分布式运行的每一个单位的信息可以完整的掌握，同时，其操作设置需满足当地电力系统的不同需求。这一类型的虚拟电厂，可以达到全局最优目标，但其可扩展性和兼容性有限。

集中式调度的优化模型从优化目标来看主要以单目标优化为主，也有研究综合考虑了用户满意度，系统安全性，电能质量以及运行成本限制等，建立了虚拟电厂模糊多目标优化调度模型[22]。单目标优化主要以虚拟电厂成本[23]-[27]最小或利润最大[29]-[39]为目标；也有研究以用户用电需求[40]最小或碳排放最小[41]为目标。虚拟电厂内的成本一般可分为以下几类：1) 边际成本[23] [24] [28]-[30]；2) 发电成本[25] [36]-[38]；3) 购电成本[26]；4) 弃电成本[27] [33]-[35]；5) 启停成本[31] [32]；6) 可中断成本[38]；7) 备用成本[39]。

虚拟电厂可以像传统发电厂一样参与到电力市场中，其参与的市场类型也多种多样。文献[3] [42]提出了虚拟电厂在电力市场运行的总体框架，文献[43] [44]则为虚拟电厂优化运行提供了一个多层协商机制，该机制可使虚拟电厂在智能电网下协调所有的发电单元与负荷，允许用户模拟日前市场池、双边合同、混合市场、平衡市场，及多个市场模型的混合等多个市场模型。电力市场下虚拟电厂调度从调度周期来看，其优化调度模型又可分为年度、月度、周度、日前、小时及实时调度。文献[45]给出的年度调度模型中以虚拟电厂年度成本最小为目标。当前虚拟电厂研究主要以日前调度为主，如文献[27]建立了含电动汽车的虚拟电厂日前调度模型；文献[46]研究了大规模虚拟电厂日前热能和电能优化调度问题。该研究中的多个虚拟电厂可从属于不同的所有者，并共同参与到电力市场中。此外，文献[47] [48]建立了以一周为周期的虚拟电厂优化调度模型，虚拟电厂需满足一周内每小时电力输送的双边合同。文献[26] [49]研究了虚拟电厂的小时调度问题。文献[26]中的虚拟电厂参与能量与二次频率控制(辅助服务)市场，其分布式电源可运行在调峰或备用模式，通过可靠性及成本指标来评估决定运行模式的转换，最终确定最优小时运行策略；文献[49]提出了不同市场环境下的优化方法以及需求侧的管理决策。文献[24]建立了虚拟电厂 30 分钟优化调度模型。文献[50]研究的虚拟电厂短期经济调度可提供能量实时平衡服务。

虚拟电厂内含大量风力、光伏等不可控分布式电源，其出力受自然影响较大，实际输出时存在很大的随机性与波动性；且虚拟电厂内的负荷及其参与到电力市场后的电价也存在一定的不确定性。虚拟电厂优化调度中对不确定性因素的处理主要集中于以下几方面。

虚拟电厂内不确定性负荷可采用统计方法和经验公式来描述[51]。不确定性电价与不可控分布式电源出力的处理，可采用点估计[52]方法建立电价与不可控分布式电源的概率模型，继而建立基于概率的优化调度模型。或通过引入风险水平[53] [54]来处理。文献[53]考虑了不确定性能源价格后来管理虚拟电厂的利润风险，并基于场景还原技术实现虚拟电厂利润最大化。文献[54]还具体分析了不同风险水平下的优化调度问题。但该研究中没有考虑风力、光伏的不确定性。文献[55]对分布式电源预测误差相关的不确定性处理是通过系统中的备用容量来实现的，该研究所建立的日前调度模型中的成本函数还考虑了需求侧可调度负荷的竞价，可再生能源义务资格证及与 UoS 相关的成本，但该研究所提出的优化调度模型中不含能量存储单元。然而储能单元在虚拟电厂中是非常重要且很有必要的，虚拟电厂内需至少含一个可控发电单元或储能单元来调节其内部的不确定性。其中，可控发电单元可为核发电单元[56]、微型热电联产单元[57]等；储能装置可为蓄电池、抽水蓄能单元[58]、电动汽车[59]-[63]等。如文献[59]利用电动汽车来平衡风力发电的不确定性，使风力参与到短期(如日前)电力市场中参与调度，使虚拟电厂在峰值电价时售电，谷值电价时储能，从而实现利润最大化的目标。文献[60]研究了含电动汽车与不含电动汽车两种场景下的虚拟电厂，对比分析了电动汽车接入后所带来的利益价值。文献[61]在实现虚拟电厂总成本最小的目标下，通过基于 V2G 用户的需求和利益，使分布式发电、需求响应及电动汽车得到了多时段的智能管理。文献[62]分析了电动汽车技术对虚拟电厂一周调度的影响。通过计算电动汽车充电站的概率分布，采用不同场景来对比对虚拟电厂经济调度的影响。为保障系统稳定性运行文献[64]还引入多标准分析来设计虚拟电厂内最优储能系统管理，最小化所需的能量存储容量，以避免投入的风力发电单元少发的电量而造成甩负荷。此外，文献[65]还从需求侧的角度出发，在整合了风力发电及柔性负荷的虚拟电厂中通过柔性负荷来补偿风力发电的不确定性。

文献[66]在日前市场环境下所建立的虚拟电厂两阶段随机优化模型中以利润最大化为目标；文献[67]在日前和平衡市场中充分考虑分布式电源与电价的不确定性以利润最大化为目标建立了基于场景的两阶段随机优化模型；文献[68]中的两阶段随机优化模型以虚拟电厂成本最小化为目标，其约束条件中除电平衡外还考虑了热平衡；文献[69]提出了一个基于利润的随机模型，可为一个风电场和水利发电联合系统提供日前运行计划，该模型用一部分的水利发电容量来补偿风力发电预测误差。该研究中的两阶段随机优化模型中还考虑了不平衡成本相关的风险，并使用条件风险价值作为风险规避准则。

4. 小结

虚拟电厂是由能量管理系统监督和控制的小型和超小型分布式发电机组、可控负荷以及能量储备的集合。虚拟电厂的拥有者和操作者可以通过由电脑运算的操作规划(称为分散能源管理系统)来获得技术、经济和生态方面的益处。虚拟电厂技术方兴未艾，是分布式电源接入电网的一种有潜力的技术手段，但是其组织构成、调度管理、运行控制等方面尚待深入研究，形成可实用化的理论框架。

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