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Published in:
IEEE Systems Journal

DOI (link to publication from Publisher):
10.1109/JSYST.2020.2964436

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Computational Tools for Modeling and Analysis of Power Generation and Transmission Systems of the Smart Grid

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***Abstract*—The traditional power generation and distribution systems will be supplanted by the Internet of Energy, which accelerates the necessity to know the appropriate computation tools to perform any research in this future smart grid arena. However, there is a plethora of computational tools in this area, which challenges the researchers to find an appropriate tool based on their research objectives. Therefore, this article presents a comprehensive study about existing simulation tools related to electrical power generation, transmission, distribution, and associated systems. It provides an overview of more than 150 simulation software in these areas. The tools are classified and discussed based on both traditional and CEN-CENELEC-ETSI smart-grid reference architecture. Typical applications, sources, availability, and strengths of each tool are listed. Each tool has its own strengths and limitations to perform a certain task, and necessary information are provided to help researchers to find an appropriate computational tool for their specific research goal.**

***Index Terms*—Computational tools, generation-transmission systems, modeling software, simulation software, smart grid.**

I. Introduction

IN FUTURE, the power system is expected to go through a major shift the way the traditional power grid has been designed and managed. Distributed small-scale renewable energy generators will supersede the bulky fossil-fuel-based power generators [1]. At the same time, new types of mobile loads such as electric vehicles (EVs) will come to the scenario. The owners of these EVs and other types of storages will act simultaneously as a consumer and seller, or alternatively known as prosumer. Prosumers will connect their energy storing devices via plug-and-play facility. Therefore, uncertainty and complexity of the system will increase. Likewise, intermittent renewable energy sources at distributed locations will add extra level of complexity to the energy management [2], [3].

The Internet-like future grid, commonly known as Internet of Energy will help prosumers to trade energy through peer-to-peer energy transfer. Its intelligent and robust management technique will connect all forms of generation either in distributed, aggregated, or small-scale renewables through a solid-state transformer [4]. Since the number of small and distributed generators along with some mobile loads will increase, it will be a real challenge to retain grid stability maintaining a tolerable power quality with a regulated power flow. Additionally, various bidirectional energy transactions from prosumers under different load dynamics, schedules, and algorithms might add risks to power quality and stability issues [5], [6]. As the complexity of the system is increasing, it is important to investigate the impacts of distributed generators, intermittent renewable sources, and mobiles loads under various dynamics. There is a plethora of simulation tools in the market. The selection of tools itself is a real challenge, even before using a tool to solve a problem. Every tool has its own strengths and limitations, which is important to know before choosing a tool for a particular research objective. This article reviews the available tools in the arena of power generation, transmission, distribution systems and their associated areas, and provides information to guide a research to easily select the best match tools.

There is a relatively small body of literature that is concerned with the systematic overview of computational tools. Previous studies [7]–[9] have explored the penetration of renewable energy sources into grid. Researchers [10] attempted to evaluate the tools related to the impact of electric vehicles to grid. Much of the previous research in [7]–[9] has been exploratory about the electrical power and energy systems computation. A recent systematic literature review [11] provided a valuable information about the selection of computational tools in the area of domestic energy management. Since the recent trends in power grid upgradation have led to a proliferation of simulation tools, therefore it has become an increasingly important topic to provide a comprehensive overview. The importance and originality of this article are as follows.

1) It explores all the available simulation tools in power generation, distribution and associated areas and provide a critical analysis. This article provides an important opportunity to advance the understanding of simulation software selection based on their availability, applications, and strengths.
2) The article categorized the tools based on the traditional and CEN-CENELEC-ETSI smart grid reference architecture. Tools are placed into various layers and segments of the reference architecture, considering their functionalities and applications.

Manuscript received April 22, 2019; revised October 3, 2019; accepted December 25, 2019. *(Corresponding author: Khizir Mahmud.)*

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This article has supplementary downloadable material available at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSYST.2020.2964436

The article is outlined as follows. Section II provides an overview of the area in which tools are considered. Section II lists the computational tools, including their typical applications, availability, and sources. Section III classifies the tools based on traditional and smart grid reference architecture, following with conclusion in Section IV.

II. List of Computational Tools

The available simulation software related to the power generation systems and their distribution are listed under various sections here. Each tool provides a short description including their availability, potential source, and typical applications. Some tools have wide range of applications; however, the typical applications related to each area are included in corresponding sections. The availability of tools is identified as commercial, limited, open source, and free to use. The use of the "*limited*" tools is restricted to a certain group, or institutions, or their availability status is not known in the references, where open source is free to use.

A. Software to Analyze Power Generation Systems

The computational tools related to the modeling of various types of power generation systems are listed in this section. The power generation systems considered both conventional and renewable energy generation systems including thermal power stations, wind power generations, hydro power generations, photovoltaics power generations, geothermal power generation, biomass-based power generation, and fuel cell and hydrogen-energy based power generation systems.

1) Thermal Power Station Modeling Tools: The tools related to the systems level modeling of the thermal power stations are listed here. Some tools have a wide range of applications; however, typical applications related to this are included here.

1) Apros
   - *Commercial*, (www.apros.fi)
   - Thermal and nuclear power-station modeling and analysis [12].
2) WASP
   - *Limited*, (www.iaea.org)
   - nuclear, biomass power generation, power plant expansion analysis [13].
3) Modelon's Thermal Power Library
   - *Commercial*, (www.modelon.com)
   - Modeling, analyzing, and optimizing thermal power plant operation [14].
4) Intertek Power Plant Computer Modeling
   - *Commercial*,(http://www.intertek.com/asset-integrity management/software/computer-modeling-power-plant/)
   - Power plant components, operation, heat transfer, fluid mechanics, materials failure, statistical analysis, operation decision optimization, optimal electricity dispatch [15].
5) PowerPlantSimulator&Designer (PPSD)
   - *Commercial*, (www.powerplantsimulator.com)
   - Thermal power plant modeling [16].
6) SimSEE
   - *Open source*, (https://sourceforge.net/projects/simsee/?source = directory)
   - Petroleum fired plants, hydro, solar, and wind power station simulation, and optimal power dispatch [17].
7) 3KEYMASTER
   - *Commercial*, (www.ws-corp.com/)
   - Nuclear, fossil-fuel, hydro-based generation systems analysis [18].
8) TRNSYS
   - *Commercial*, (www.trnsys.com)
   - Solar thermal power plant, wind and PV systems, geothermal heat pump, and building simulation, optimization [19].
9) EnergyWin
   - *Commercial*, (https://criepi.denken.or.jp/en/energy/research/research11.html)
   - Thermal efficiency calculation of various power plant [20].
10) IPSEpro
    - *Commercial*, (http://simtechnology.com/CMS/index.php/ipsepro)Power plant design, analysis, and operation [21].

2) Wind Power Generation Modeling Tools: The computational tools related to the wind power generation systems modeling, analysis, and their grid integration are discussed in this section.

1) WAsP
   - *Commercial*, (www.wasp.dk)
   - Modeling and analysis of grid-connected wind power systems [22].
2) URBAWIND, RT WINDMAP, METEODYN WT
   - *Commercial*, (www.meteodyn.com)
   - Wind power monitoring, forecasting and optimization, wind farm management [23].
3) Openwind
   - *Commercial*, (https://aws-dewi.ul.com/software/openwind/)
   - Design and optimization of wind-power-based projects [24].
4) SimWindFarm
   - *Free to use*, (www.ict-aeolus.eu/SimWindFarm)
   - Control and analysis of wind power systems [25].
5) windPRO
   - *Commercial*, (www.emd.dk/windpro)
   - Modeling and analysis of wind-farm [26].
6) WndScreen3
   - *Commercial*, (www.umass.edu/windenergy/research/topics/tools/software/wndscreen3)
   - Designing and analysis of wind and diesel-based power systems [27].
7) WindSim
   - *Commercial*, (www.windsim.com)
   - Modeling and optimization of wind-farm [28].
8) WindStore
   - *Commercial*, (www.integralanalytics.com)
   - Grid-connected wind power systems analysis [29].
9) WILMAR Planning Tool
   - *Commercial*, (www.wilmar.risoe.dk)
   - *Modeling, analysis, and forecasting of wind power systems [30].*

3) Hydro Power Generation Modeling Tools: This section lists the available computational tools that focus on the system-level modeling and analysis of hydro power generation systems.

1) APS, PC-VALORAGUA
   - *Limited*, (https://ceeesa.es.anl.gov/projects/PowerAnalysisTools.html#aps)
   - Optimal control of hydroelectric power generation systems and production cost analysis [31].
2) EOPS, Samnett, Samlast
   - *Commercial*, (www.sintef.no/en/)
   - Scheduling and expansion planning of a long-term and short-term hydro power generation [32].
3) Hydro-Clone
   - *Commercial (free for academics)*, (www.powervision-eng.ch/HydroClone/MainFeaturesHydroClone.html)
   - Hydro power systems modeling and analysis [33].
4) Hydro Power Library
   - *Commercial*, (www.modelon.com)
   - Hydro power plant modeling and control [34].
5) MAXHYDRO
   - *Commercial*, (www.maxhydro.com)
   - Real-time monitoring, modeling, and optimization of hydro-power systems [35].
6) OptiPower
   - *Commercial*, (www.powervision-eng.ch/OptiPower/MainFeatures.html)
   - Modeling and management of hydropower generation [36].
7) SHOP, SHARM
   - *Commercial*, (www.sintef.no/en/)
   - Modeling and optimization of hydropower generation [37].
8) SIMSEN, SIMSEN-Hydro
   - *Commercial*, (http://simsen.epfl.ch/)
   - Modeling and analysis of hydropower systems, distribution networks, load flow [38].

4) Photovoltaics Power Generation Tools: The simulation software to model the photovoltaics-based power generation systems and their management are discussed in this section.

1) Archelios
   - *Commercial*, (www.trace-software.com)
   - PV systems and PV project modeling and analysis [39].
2) easy-pv
   - *Free to use*, (http://easy-pv.co.uk/)
   - Modeling and analysis of PV systems [40].
3) METEODYN PV
   - *Commercial*, (www.meteodyn.com)
   - Modeling and analysis of a large-scale PV power generation, optimization, and PV layout design [41].
4) PV F-CHART
   - *Commercial*, (www.fchart.com/pvfchart)
   - Design and analysis of comprehensive PV systems [42].
5) PV∗SOL
   - *Commercial*, (www.valentin-software.com/en)
   - Small-scale and large-scale modeling of PV power generation systems, PV-attached battery systems and their cost-benefits [43].
6) PVWatts
   - *Free to use*, (http://pvwatts.nrel.gov/)
   - Grid-connected PV systems modeling and analysis [44].
7) SAM
   - *Free to use*, (https://sam.nrel.gov)
   - Economic analysis of PV systems along with other renewable sources [45].
8) Solar Pro
   - *Commercial*, (www.lapsys.co.jp)
   - Small-scale residential PV systems design and analysis [46].
9) Pvcad
   - *Free to use*, (www.iset.uni-kassel.de/pvcad)
   - Grid-connected PV systems modeling [47].
10) PVSYST
   - *Commercial*, (www.pvsyst.com)
   - Grid-connected and stand-alone PV systems modeling and analysis [48].
11) SolarDesignTool
   - *Commercial*, (http://get.solardesigntool.com)
   - An online tool to model and analyze PV systems [49].

5) Geothermal Power Generation Tools: Geothermal power stations are also getting popularity in some locations along with conventional generation systems. So, this section focuses on the available simulation tools that focus on the modeling and analysis of geothermal power generation systems.

1) COMSOL Multiphysics
   - *Commercial*, (www.comsol.com)
   - Modeling and analysis of geothermal energy [50].
2) FALCON
   - *Open Source*, (https://github.com/idaholab/falcon)
   - Modeling of geothermal energy [51].
3) GeoCube
   - *Commercial*, (www.precisiongeothermal.com)
   - Data analysis of geothermal energy systems [52].
4) GeoLogik
   - *Commercial*, (www.geologik.com/sf)
   - Geothermal energy systems modeling [53].
5) GeoModeller
   - *Commercial*, (www.intrepid-geophysics.com)
   - Geothermal-based power generation systems analysis [54].
6) GeoT∗SOL
   - *Commercial*, (www.valentin-software.com/en)
   - Geothermal-based power systems modeling and analysis [43].
7) HyGCHP
   - *Free to use*, (www.seventhwave.org/hygchp)
   - Geothermal energy systems analysis [55].
8) RETScreen
   - *Free to use*, (www.nrcan.gc.ca/energy/software-tools/7465)
   - Geothermal, renewable and clean energy systems modeling [56].
9) SHEMAT
   - *Commercial*, (http://www.gge.eonerc.rwth-aachen.de/cms/E-ON-ERC-GGE/Forschung/Ausstattung/∼fqun/Shemat-Software/?lidx = 1)
   - Analysis of geothermal energy systems [57].
10) SVHeat
   - *Commercial*, (www.svheat.com)
   - Modeling and analysis of geothermal energy [58].

6) Biomass-Based Power Generation Tools: This section presents the software that deals with the modeling, analysis, energy conversion, and distribution of biomass-based energy generation systems.

1) IPSE pro

- *Commercial*, (www.simtechnology.com/CMS/index.php/ipsepro)
- Modeling and analysis of biomass-based energy generation [21].

2) BSM
- *Free to use*, (http://en.openei.org/wiki/Biomass_Scenario_Model)
- Modeling and analysis of biomass power generation, conversion, and distribution [59].

3) H_2RES
- *Limited*, (http://h2res.fsb.hr)
- Modeling, analysis, planning, and management of biomass energy [60].

4) BIOBIL, BAUM
- *Commercial*, (www.bios-bioenergy.at/en/)
- Biomass energy systems modeling and analysis [61].

7) Fuel Cell and Hydrogen Energy-Based Power Generation Tools: Fuel cell and hydrogen energy are an alternate mode of power generation systems. So, this section discusses the available energy simulation software to model and analyze hydrogen and fuel cell-based power generation systems.

1) Fuel Cell Library
- *Commercial*, (www.modelon.com)
- Fuel cell-based power generation systems modeling and analysis [62].

2) FCPower
- *Limited*, (www.hydrogen.energy.gov/fc_power_analysis.html)
- Fuel cell systems and their finance analysis [63].

3) HYDROGEMS
- *Limited*, (https://www.energyplan.eu/othertools/local/hydrogems/)
- Modeling and analysis of hydrogen systems and its interface to other types of energy systems [64].

4) Easy5
- *Commercial*, (www.mscsoftware.com/product/easy5)
- Fuel cell design and analysis [65].

5) ANSYS CFD
- *Commercial*, (www.ansys.com)
- Analysis of fuel cell-based energy systems [66].

B. Software Related to Power Transmission and Distribution Systems

This section gathered the simulation software that are related to the modeling and analysis of transmission/distribution systems. Most common applications of these software are ac and dc transmission/distribution systems design, control, and monitoring of power networks and their management, analysis of short circuit, power flow, and power quality.

1) ATP
- *Commercial*, (www.emtp.org)
- Analysis and control of complex power networks [67].

2) CASPOC
- *Commercial*, (http://www.caspoc.com)
- Power generation and distribution systems analysis [68].

3) Cymdist
- *Commercial*, (http://www.cyme.com/software/cymdist/)
- Power distribution systems analysis [69].

4) EDSA Paladin Toolkit
- *Commercial*, (https://www.poweranalytics.com/paladin-software/paladin-designbase-5-0-features/)
- AC and DC power distribution systems analysis [70].

5) OpenDSS
- *Open source*, (www.electricdss.sourceforge.net)
- Modeling of electrical distribution systems [71].

6) PADEE
- *Commercial*, (http://padeepro.com/padeeing.html)
- Small-scale distribution network, demand forecast and protection systems analysis [72].

7) PSLF
- *Commercial*, (https://www.geenergyconsulting.com/practice-area/software-products/pslf)
- Power distribution systems analysis [73].

8) Synergi Electric
- *Commercial*, (www.dnvgl.com)
- Power distribution systems design and analysis [74].

9) ReticMaster/PowerOffice
- *Commercial*, (www.reticmaster.com)
- low-voltage network, power quality, and energy management analysis [75].

10) DSATools
- *Commercial*, (www.dsatools.com)
- Power systems and stability analysis [76].

11) PSS NETOMAC, PSS/E, PSS SINCAL
- *Commercial*, (https://new.siemens.com/global/en.html)
- Power transmission and distribution systems, power quality, dynamics, stability, power flow, power systems optimization, monitoring, control, protection systems, and reliability analysis [77].

12) ETAP toolkit
- *Commercial*, (www.etap.com)
- Power transmission and distribution systems, power quality, control, dynamics, renewable energy integration, network optimization, fault analysis, protection systems, grounding, and cable analysis [78].

13) EMTP-RV
- *Commercial*, (https://www.emtp-software.com/page/overview)
- large-scale power networks, load-flow and harmonics analysis [79].

14) AGORA
- *Commercial*, (www.elequant.com/products/agora)
- Power quality, power distribution and their monitoring analysis [80].

15) CYME Tool kit
- *Commercial*, (cyme.com)
- Power quality, transmission/distribution systems, transformer, protection [81].

16) GridLAB-D
- *Open source*, (www.gridlabd.org)
- Transmission/distribution systems, renewable energy integration, customers' behavior analysis [82], [83].

17) IPSA
- *Commercial*, (www.ipsa-power.com)
- Power distribution network, power quality, power flow, fault, and protection systems analysis [84].

18) GridSpice
- *Open source*, (https://code.google.com/p/gridspice/)
- Smart grid modeling and analysis [85].

19) MiPower
    - *Commercial*, (http://www.prdcinfotech.com/business/software-engineering-group/software-products/mipower-subscribe/)
    - Power networks analysis [86].
20) Mosaik
    - *Open source*, (https://mosaik.offis.de/install/)
    - Simulation of smart grid simulation with larger size [87].
21) POM Applications Suite
    - *Commercial*, (www.vrenergy.com)
    - Power transmission systems, monitoring, power quality and stability analysis [88].
22) PowerFactory
    - *Commercial*, (www.digsilent.de)
    - Power distribution systems modeling, monitoring and control, stability and power quality analysis [89]–[92].
23) MatNetFlow, PST, MatNetEig
    - *Available on request*, (www.eps.ee.kth.se/personal/vanfretti/pst/Power_System_Toolbox_Webpage/PST.html)
    - Power systems (large-scale) modeling, analysis, and control [93].
24) VOLTTRON
    - *Free to use*, (https://github.com/VOLTTRON/volttron)
    - Distributed renewables integration to grid, vehicle charging, building energy efficiency analysis [94].
25) Simpow
    - *Commercial*, (http://simpow.com)
    - Power transmission and distribution, short circuit, and stability analysis [95].
26) Grid360 (Grid360 Transmission Analytics, Grid360 Distribution Analytics)
    - *Commercial*, (https://www.nexant.com/software/grid360)
    - Transmission and distribution systems modeling and analysis, optimization, optimal power flow and fault location analysis, distributed energy resources, contingency analysis [96].

C. Tools for Model and Analyze Transformer and Substation

As transformer and substation systems are an essential component of power transmission and distribution systems, this section accumulated available simulation software that can model and analyze transformers and substations. The typical applications of transformer-related software in this section are design, analyze, and optimize the modeling of the transformer, perform various performance test of the transformer, and checking of different thermal conditions.

1) Opera transformer design software
    - *Commercial*, (https://operafea.com/transformer-design-software)
    - Analysis of transformer efficiency, inductances, flux distribution in the core, short-circuit and open-circuit analysis, inrush current/load test, loess, EMC/EMI, dynamic forces on coils, etc. [97].
2) PowerEsim
    - *Free to use*, (https://infineon.poweresim.com/)
    - An online tool to simulate transformer windings, thermal conditions, losses, types of transformers in various applications [98].
3) EMS
    - *Commercial*, (www.emworks.com/product/EMS)
    - Electrical and magnetic field modeling and analysis including transformers [99].
4) ANSYS Maxwell
    - *Commercial*, (www.ansys.com/products/electronics/ansys-maxwell)
    - Design and analysis of transformer [100].
5) Power Supply Designer, Magnetics Designer
    - *Commercial*, (www.intusoft.com/mag.htm)
    - Analyze, design and optimize transformers and inductors from electrical applications [101].
6) MagNet
    - *Commercial*, (www.infolytica.com/en/products/magnet/)
    - Electromagnetic field simulation including transformers [102].
7) QuickField
    - *Free student version*, (https://quickfield.com/index.htm)
    - Transformer design specially ac magnetics, transient magnetics, heat transfer and stress analysis [103].

D. Tools to Model and Analyze Substation

The substation systems design tools deal with the physical layout, substation grounding, protection and control systems analysis.

1) Bentley Substation
    - *Commercial*, (www.bentley.com)
    - Modeling of substation systems, their protection and control [104].
2) Primtech
    - *Commercial*, (www.primtech.com)
    - substation protection, control, and physical layout design and analysis [105].
3) Enhanced Substation Modeling
    - *Commercial*, (www.cyme.com)
    - Substation grounding design [81].
4) AUTODESK Substation Design
    - *Commercial*, (www.substationdesignsuite.com)
    - Substation protection, control and physical layout modeling [106].
5) Substation Explorer
    - *Commercial*, (www.abb.com)
    - 3-D layout design, troubleshoot of substation automations and financial analysis [107].

E. Software Related to the Overhead and Underground Cables, and Grounding

The overhead and underground cables, and grounding have an impact on the overall transmission and distribution systems modeling. So, this section provides a list of available simulation tools that can analyze various types of cables having different size, capacity, and characteristics considering standards.

1) CYMCAP
    - *Commercial*, (www.cyme.com)
    - Analysis of the cable size, capacity, temperature effect, and magnetic field [81].
2) Cable Pro
    - *Commercial*, (https://elek.com.au/electrical-software/elek-cable-pro-au)

- Analysis of the cable size, capacity, protection, reliability and standards [108].

3) etap cable systems tool
   - *Commercial*, (www.etap.com)
   - Analysis of the cable size, capacity, reliability and standards [78].
4) TRALIN
   - *Commercial*, (www.sestech.com)
   - Cable sizing, constrains, electromagnetics analysis [109].
5) QuickCable
   - *Commercial*, (http://www.powercad.com.au/quick cable_lt.php)
   - Design and analysis of the cable size and capacity [110].
6) ASPEN Line Constants Program
   - *Commercial*, (www.aspeninc.com/web/software/line-constants)
   - Transmission lines cable capacity, constrains analysis [111].

F. Tools for Model and Analyze Grounding

1) WinIGS
   - *Commercial*, (www.ap-concepts.com)
   - Power systems grounding, fault, lightning analysis [112].
2) SafeGrid Earthing
   - *Commercial*, (https://elek.com.au/electrical-software/elek-safegrid-earthing/)
   - Power grid earthing design and analysis [113].
3) CDEGS
   - *Commercial*, (www.sestech.com/products/soft packages/cdegs.htm)
   - Power systems grounding and electromagnetics analysis [114].
   - Safearth
     Commercial, (www.safearth.com)
   - Power systems earthing analysis [115].
4) XGSLab
   - *Commercial*, (https://www.neplan.ch/neplanproduct/grounding-design/)
   - Electrical grounding, power quality analysis [116].
5) SKM GroundMat
   - *Commercial*, (http://www.skm.com/groundMat.html)
   - Substation grounding design and analysis [117].
6) CYMGRD
   - *Commercial*, (www.cyme.com)
   - Sub-station grounding design [81].
7) Etap System Grounding & Earthing Analysis
   - *Commercial*, (www.etap.com)
   - Power systems grounding analysis [78].
8) AutoGroundDesign
   - *Commercial*, (http://www.sestech.biz/Software Products.html)
   - Power systems grounding analysis [118].
9) KWIKGRID, TACLINK
   - *Commercial*, (www.ground-it.com/software.htm)
   - Substation and power system grounding analysis [119].
10) GSA
    - *Commercial*, (www.xgslab.com/index.php/en/gsa)
    - Low-frequency grounding systems design [120].

G. Tools for Model and Analyze Distributed Energy Resources

Various type of small-scale distributed energy resources (DERs) is being widely used in modern power systems. So, this section provides an overview of specialized software that deals with the integration DERs into the grid, and perform their characteristic analysis.

1) GridLAB-D
   - Open source, (https://www.gridlabd.org/index.stm)
   - Distributed energy resources modeling and analysis [82], [83].
2) Etap toolkits
   - Commercial, (www.etap.com)
   - Power transmission and distribution systems, power quality, control, dynamics, renewable energy integration, network optimization, fault analysis, protection systems [78].
3) Smart Grid Analytics
   - Commercial, (www.itron.com)
   - Analyze distributed generation systems, grid reliability, operation efficiency, and customers engagement [121].
4) RAPSim
   - Open source, (https://sourceforge.net/projects/rapsim)
   - Modeling the grid control systems while integrating storage and renewables and simulate microgrids [122], [123].
5) IDROP
   - *Commercial*, (http://www.integralanalytics.com/products -and-services/smartgrid-solutions/idrop.aspx)
   - Simulate distributed energy sources [124].
6) iGRHYSO
   - Commercial, (www.unizar.es/rdufo/grhyso.htm)
   - Simulate Distributed generation systems, storages, electric vehicles, and optimize grid-connected renewables [9].

H. Power Flow and Short-Circuit Analysis Tools

This section lists the simulation tools that are appropriate to conduct power flow and short-circuit analysis of power systems.

1) ALF
   - *Limited*, (http://ceeesa.es.anl.gov/projects/Power AnalysisTools.html)
   - Power flow for both real and reactive power and system response analysis [125].
2) ARTERE
   - *Limited*, (www.montefiore.ulg.ac.be/∼vct/software.html)
   - Analysis of power flow [126].
3) CERBERUS
   - *Commercial*, (https://www.adapted-solutions.com/en/produkte-2/cerberus/)
   - Load-flow and short-circuit analysis [127].
4) LOADSYN, DYNRED, IPFLOW
   - *Limited*, (www.eee.hku.hk/∼cees/software/psapac.htm)
   - Load and power flow, dynamics stability, and small-signal analysis [128].
5) Fendi
   - *Open source*, (www.martinole.org/Fendi)
   - Load-flow and ac/dc distribution systems analysis [129].

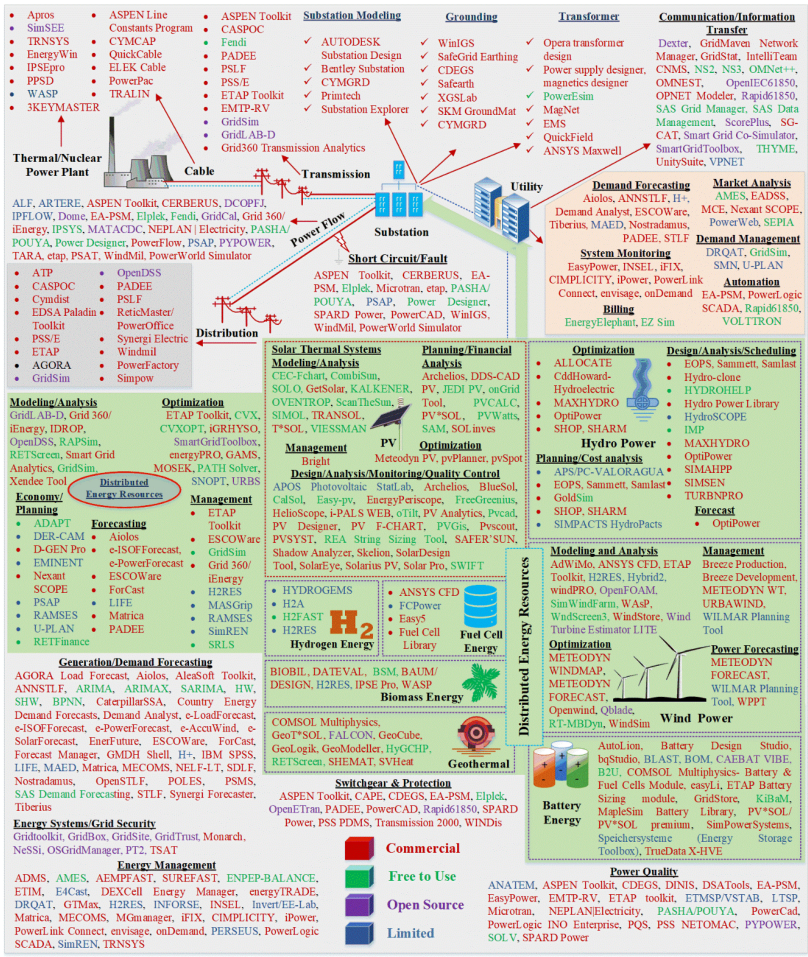

Fig. 1. Simulation software for the power generation, and their transmission and distribution systems arranged using the traditional grid architecture [167].

6) IPSYS
   - *Free to use*, (www.ece.cmu.edu/∼nsf-education/software.html)
   - Load-flow analysis [130].
7) MatDyn
   - *Open source*, (https://www.swmath.org/software/21550)
   - Power-flow and dynamics analysis [131].
8) PSAP
   - *Limited*, (www.eng.auburn.edu/∼gross/readme.htm)
   - Power-flow, fault, and economic dispatch of power analysis [132].
9) RPowerLABS
   - *Free to use (academics)*, (www.rpowerlabs.org)
   - Stability, fault and power-flow analysis [133].
10) PowerWorld Simulator
   - *Commercial*, (www.powerworld.com)
   - Power flow and power quality analysis [134], [135].
11) etap toolkits
   - *Commercial*, (www.etap.com)
   - Load flow, short circuit, automation, protection, transmission lines [78].
12) ANAFAS, Encad, PacDyn, ANATEM, ANAREDE, FLUPOT, HarmZs
   - *Limited*, (www.cepel.br)
   - Power flow, short circuit, transient, reliability, distribution network analysis [136].
13) DCOPFJ
   - *Open source*, (www2.econ.iastate.edu/tesfatsi/DCOPFJHome.htm)
   - Electrical power flow (dc) analysis [137].
14) GridCal
   - *Open source*, (https://github.com/SanPen/GridCal)
   - Electrical power-flow analysis [138].
15) MATACDC
   - *Open source*, (www.esat.kuleuven.be/electa/teaching/matacdc)
   - Power-flow analysis for both ac and dc [139]–[141].
16) EasyPower Suites
   - *Commercial*, (www.easypower.com)
   - Power-flow, control and distribution systems analysis [142].
17) PYPOWER-Dynamics/PYPOWER
   - *Open source*, (https://github.com/rwl/PYPOWER)
   - Transient stability, and power flow for both AC and DC [143].
18) UWPflow
   - *Open source*, (https://uwpflow.software.informer.com/)
   - Voltage stability and power-flow analysis [144].
19) PSAT
   - *Free to use*, (http://faraday1.ucd.ie/psat.html)
   - Optimal flow of power, small-signal, power quality analysis [145].

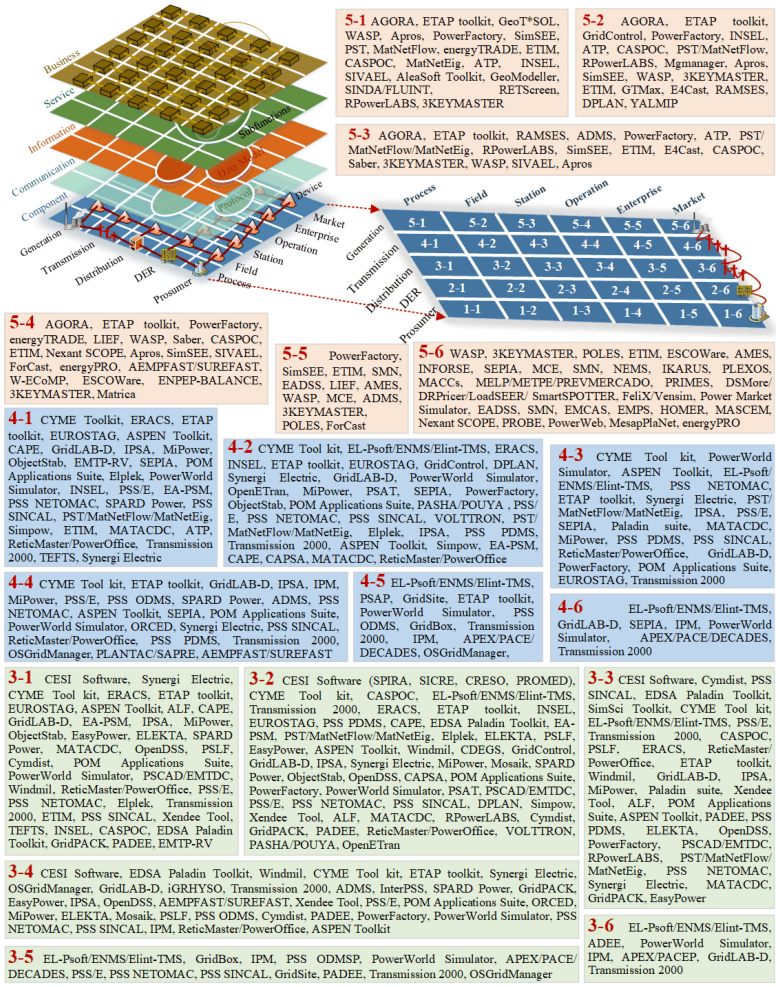

Fig. 2. Simulation software for the power generation, transmission, and distribution systems arranged using the smart grid reference architecture [167].

20) CYME Tool kit
   - *Commercial*, (cyme.com)
   - Load flow, power flow, fault, stability, transient analysis [81].
21) WindMil
   - *Commercial*, (www.milsoft.com)
   - Power flow, short circuit, fault, voltage drop, arc flash hazard, and reliability analysis [146].

I. Tools to Analyze Power Quality and Stability

While designing power transmission/distribution systems, thorough investigation of power quality and system stability is essential. So, this section reviews the available software for power quality and stability analysis.

1) CDEGS
   - *Commercial*, (www.sestech.com)
   - Transient, electromagnetics, and protection systems analysis of power distribution systems [114].
2) DINIS
   - *Commercial*, (www.dinis.com)
   - Transient stability, reliability, protection systems and load management analysis [147].
3) EMTP-RV
   - *Commercial*, (www.emtp-software.com)
   - Harmonics, load flow and large network analysis [79].
4) EL-Psoft, ENMS, Elint-TMS
   - *Commercial*, (www.nexgenconsultancy.com)
   - Power quality, load flow analysis [153].
5) SOLV
   - *Commercial*, (www.mirusinternational.com/solv.php)
   - Power quality analysis [152].
6) PASHA/POUYA
   - *Free to use*, (www.tomcad.com)
   - Harmonics, protection systems, transient stability, reliability, power flow, load flow, short circuit and renewable energy integration analysis [149].
7) EMTDC, PSCAD
   - *Available free version*, (www.hvdc.ca/pscad)
   - Power networks, control, and power quality analysis [154].
8) PSASP, VSTAB, ETMSP, SSSP, LTSP
   - *Limited*, (www.eee.hku.hk/∼cees/software/psapac.htm)
   - Harmonics, power network and voltage stability, power flow, small-signal analysis [128].
9) PQS
   - *Commercial*, (https://pqs.schaffner.com)
   - Power quality and harmonics analysis [151].
10) Etap toolkits
   - *Commercial*, (www.etap.com)

– harmonics, short circuit, load flow, stability [78].

11) Power∗Tools
   – *Commercial*, (www.skm.com)
   – Power quality and fault analysis [150].
12) CYME Tool kit
   – *Commercial*, (cyme.com)
   – Power quality analysis (harmonics, load flow, fault, stability, transient, volt-var optimization, electromagnetics etc) [81].
13) NEPLAN | Electricity
   – *Commercial*, (https://www.neplan.ch/neplanproduct/en-electricity/
   – Power systems transient, reliability, power flow, renewable energy integration, and smart grid analysis [148].

J. Tools to Analyze Protection Systems

Due to the complex power flow, while integrating distributed energy resources, various types of protection systems are required. This section provides an overview of available simulation tools that can model and analyze protection systems.

1) ASPEN Toolkit
   – *Commercial*, (www.aspeninc.com)
   – Protection systems, relay coordination, and balanced–unbalanced system analysis [155].
2) CAPE
   – *Commercial*, (www.electrocon.com)
   – Analysis of the power grid protection systems [156].
3) EA-PSM
   – *Commercial*, (http://www.energyadvice.lt/en/electrical-engineering-software-for-plant/
   – Power systems protection, automation, short circuit, load flow, and harmonics analysis [157].
4) EasyPower Suites
   – *Commercial*, (www.easypower.com)
   – Power systems protection, automation, short circuit, load flow, and harmonics analysis [142].
5) Elplek
   – *Free to use*, (http://elplek.allapp.biz/)
   – Power systems protection, load flow, and short-circuit analysis [158].
6) OpenETran
   – *Open source*, (https://github.com/epri-dev/OpenETran)
   – Protection systems analysis (lightning protection, insulation, and surge arrestor) [159].
7) CYME Tool kit
   – *Commercial*, (cyme.com)
   – Power grid protection systems modeling, analysis and management [81].
8) PSS PDMS
   – *Commercial*, (www.siemens.com)
   – Management of the power systems protection devices [160].
9) PowerCAD, WINDis
   – *Commercial*, (http://www.fractal.hr/eng/software/applications.html)
   – Designing and analysis of the protection systems, short circuit, and power flow and distribution networks [161].

TABLE I
COMPARATIVE STUDY BETWEEN COMMONLY USED TOOLS IN THE POWER GENERATION, TRANSMISSION, AND DISTRIBUTION RELATED AREAS

Applications / Tools	Thermal power generation systems	Renewable energy integration	Substation, transformer and grounding design	Transmission and distribution systems design	OH and UG Cables	Switchgear and Protection Systems	Power Quality	Power Flow and short Circuit
PowerFactory	×	√	×	√	×	√	√	√
PSCAD	×	√	×	√	×	√	√	√
PSS/E	×	√	×	√	×	√	√	√
WindSim	×	√ (wind only)	×	×	×	×	×	×
OptiPower	×	√	×	√	×	×	×	×
Solar Pro	×	√ (solar only)	×	√	×	×	×	×
IPSE Pro	√	√	×	×	×	×	×	×
ATP	×	√	√	√	√	√		√
EDSA Paladin Toolkit	×	√	√	√	√	√	√	√
OpenDSS	×	√	√	√	√	×	√	√
ETAP toolkit	×	√	√	√	√	√	√	√
CYME Tool kit	×	√	√	√	√	×	√	√
POM Applications Suite	×	√	×	√	×	×	×	√
AUTODESK Substation Design	×	×	√	√	√	×	×	×
GridLAB-D	×	√	×	√	×	×	×	√
Power World Simulator	×	√	√	√	×	×	×	√
ASPEN Toolkit (DistriView)	×	√	√	√	√	√	√	√
Power CAD, WINDis	×	×	√	√	√	√	√	√
EMTP-RV	×	√	√	√	×	√	√	√
Easy Power Suites	×	×	×	×	×	√	√	√
CYMGRD	×	×	×	×	√	×	×	√
Cable Pro	×	×	×	×	√	√	×	×
ANSYS Maxwell	√	√	√	√	√	√	√	√
Bentley Substation	×	×	√	√	√	√	×	√
POM Applications Suite	×	×	×	√	×	×	×	√
Grid Spice	×	√	√	√	√	√	√	√
IPSA	×	√	√	√	√	√	√	√

OH: overhead, UG: underground.
Note: only system level applications are considered, not component level.

10) PowerCad-5, PowerCalc-H, PowerCalc, QuickCable
   – *Commercial*, (www.powercad.com.au)
   – Modeling and analysis of the protection systems, power factor, stability, harmonics, and power distribution systems [161], [162].
11) SPARD Power
   – *Commercial*, (www.energyco.com)
   – Optimization of the protection systems, and analyze harmonics, transient stability, reliability, short circuit and load flow [163].

III. CLASSIFICATION OF TOOLS BASED ON TRADITIONAL AND SMART GRID ARCHITECTURE

The tools listed in Section III are arranged based on the traditional grid architecture, as shown in Fig. 1. The grid architecture includes all the components related to the generation and their distribution systems such as conventional and renewable power generation systems, overhead and underground

cables, substations, transformer, distributed energy resources, and utilities. Each tool is color coded based on their availability. Computational tools are further classified based on the Smart Grid Reference Architecture, as shown in Fig. 2. The architecture by CEN-CENELEC-ETSI Smart Grid Coordination Group includes five layers, five domains, and six zones [164]–[167]. Simulation software is arranged following these layers, zones, and domains that are relevant to the generation, transmission, and distribution systems, as shown in Fig. 2. Some tools related to the power generation, transmission, and distribution and associated areas, which covers most of the layers, zones, and domains in Fig. 2 are listed in Table I and their application horizon are noted. It is found that some tools such as PowerFactory, PSCAD, PSS/E, Etap, and CYME toolkit are widely used tools covering a wide range of applications in the power generation, transmission, and distribution systems related areas.

IV. Conclusion

The purpose of this article was to provide a comprehensive overview of the available simulation tools in power generation, its distribution and associated areas. Various surveys in this article suggest that a significant number of computational tools related to power generation, transmission, distribution, and related areas are available. So, researchers face tool selection challenge to accomplish their research objectives. A comprehensive overview with necessary information is provided to enhance the understanding about tools. The review finds that some tools have a wide range to applications such as PowerFactory, PSCAD, PSS/E, ETAP, and ATP toolkit. The number of available simulation tools to simulate renewable energy sources such as wind and solar is relatively higher than that of the traditional thermal power station simulations tools. The findings of this article suggest that a wide range of study requires a combination of various tools. It is hoped that this article will contribute to a deeper understanding about the selection of an appropriate tool for a specific research goal.

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