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An Overview

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Standard Test Systems for Modern Power System Analysis: An Overview

Saeed Peyghami, *Member IEEE*, Pooya Davari, *Senior Member IEEE*, Mahmud Fotuhi-Firuzabad, *Fellow IEEE*, and Frede Blaabjerg, *Fellow IEEE*

Abstract –Reliable design, planning and operation of power systems are of paramount importance to ensure providing reliable services to customers. This paper reviews the different aspects of power system reliability from planning to operation. Afterwards, standard benchmarks employed for power system studies are reviewed according to almost 2,500 journal publications in the IEEE since 1986 to early 2019. The present overview shows the pros and cons of the existing test systems implying the lack of appropriate benchmarks for future power system studies including renewable resources and modern technologies. Furthermore, this paper presents requirements for updating and modifying the benchmarks for modern power systems analysis.

Index: power system, smart grids, operation, reliability, security, stability, test systems, IEEE standard test systems, CIGRE benchmarks, DC benchmarks, reliability benchmarks.

I. INTRODUCTION

Modern technologies in particular, variable energy resources and distributed generations such as Photo-Voltaic (PV) and wind energy, e-mobility, and most recently, distributed storages, Direct Current (DC) based transmission and distribution systems, together with smart grid concepts are revolutionizing the electrical power systems worldwide [1], [2]. Power systems are becoming as distributed as possible in both physical and cyber layers [1], [3]. In the physical layer, power electronics plays a significant role in the energy conversion process in generation, transmission, distribution and consumption levels. Furthermore, paradigm shift from top-down manner to the distributed one highlights the importance of communication systems in planning and operation of modern power systems. On the other hand, electrical networks are one of the most critical infrastructures and the most complex systems, in which, any accident or outage might introduce irrecoverable socioeconomic consequences. The modernization and liberalization aiming to efficiency and performance enhancement even make it more complex and vulnerable and being exposed to reliability, security and cyber-security issues.

Operation and planning of such a complex system with different dynamics require deep analyses considering various phenomena. These analyses comprise of power system planning issues such as marketing, energy management, power flow and optimal power flow control, and operation issues such as stability and protection. The wide range of analyses regarding planning and operation are generally carried out to strengthen the power systems performance. The best performance will be deduced if the system is planned and operated economically with a reasonable level of reliability taking into account uncertainties in generation, load, outages and accidents. To evaluate and improve the system performance beside economic studies, the system reliability assessment is of paramount significance.

System performance evaluation and enhancement require establishing some techniques, methods, tools, algorithms, and concepts for different phenomena. For a complex system, the viability of solutions as well as validating the techniques should be examined through agreed test systems. Different test systems, IEEE and CIGRE benchmarks in particular, have been introduced for power system analysis. These systems are available from small to large scale at various voltage and power levels.

The benchmarks can be used for analysis of power system reliability, stability, protection, power quality, marketing, planning, observability, optimization and etc. So far, the standard test systems have been employed for conventional grid analysis with centralized, top-down generation and control systems. However, modern power systems analysis needs new benchmarks to address modern technologies and their associated issues in power system studies.

The test systems for reliability evaluation have been reviewed identifying 240 journal papers in [4]. The most focus of that review was on the main concepts of reliability, i.e., adequacy and security. However, power system reliability can be affected by wide range of phenomena, which may deteriorate the system reliability and shift it to an insecure region. Therefore, reliable operation and planning of power systems require studying its different aspects. This paper classifies different power system concepts from design to operation including reliability, stability, control and so on.

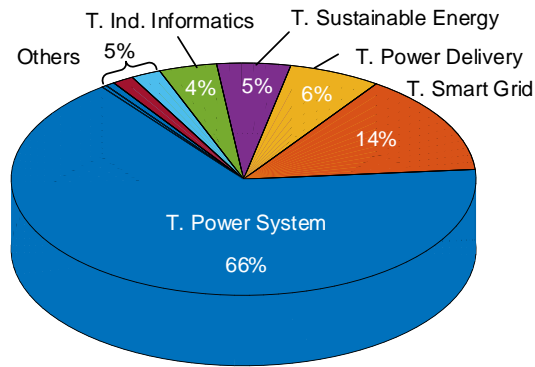


Fig. 1. Statistics of reviewed IEEE journal Transactions (T.) discussing test systems.

Afterwards, the existing standard test systems are reviewed and the use of standard benchmarks for different power system studies are investigated identifying almost 2,500 related journal papers since 1986 to early 2019 from the following journals:

- IEEE Transactions on Power Systems
- IEEE Transactions on Power Delivery
- IEEE Transactions on Energy Conversion
- IEEE Transactions on Sustainable Energy
- IEEE Transactions on Smart Grid
- IEEE Transactions on Industrial Informatics
- IEEE Transactions on Industry Applications
- IEEE Transactions on Industrial Electronics
- IEEE Transactions on Power Electronics

Fig. 1 shows the contribution of the aforementioned journals on the reviewed papers of this work. In the following, Section II reviews the power system analysis concepts. Then the standard test systems and their applications in different areas are presented in Section III and Section IV, respectively. Section V presents the pros and cons of the existing test systems. The modern power system challenges and the recommended requirements for modifying the test systems are discussed in section VI. Finally, the paper is summarized in Section VII.

II. MULTI-TIME SCALE POWER SYSTEM ANALYSIS

Power system planning and operation are set processes of optimal and economical design, expansion, monitoring, management, protection and control of electrical networks in order to supply end consumers with a desired level of reliability. It requires various studies in different time scales from microseconds to even several years. Power system studies can generally be studied in three major time frames including long-term facility planning (so-called expansion planning), short-term operational planning and real-time operation as shown in Fig. 2.

Long term dynamics are associated with the planning, where it can be divided into two categories. The first one is the facility planning and the second one is the operational planning [5]. The time of interest for facility planning is 5 to 30 years and for the operational planning is from a few minutes to 1 year [6]. The aim of facility planning is to optimally and economically develop power systems such as addition of generation units, expansion and reinforcement of transmission, distribution networks considering load growth within a specific time. On the other hand, operational planning refers to optimal and economical employment of the existing facilities to reliably supply the load at the real time. Furthermore, power system operation refers to continuously monitoring, operating and control of facilities in order to appropriately maintain the normal operating state. The ultimate goal is to ensure a certain level of reliability per cost in supplying end consumers.

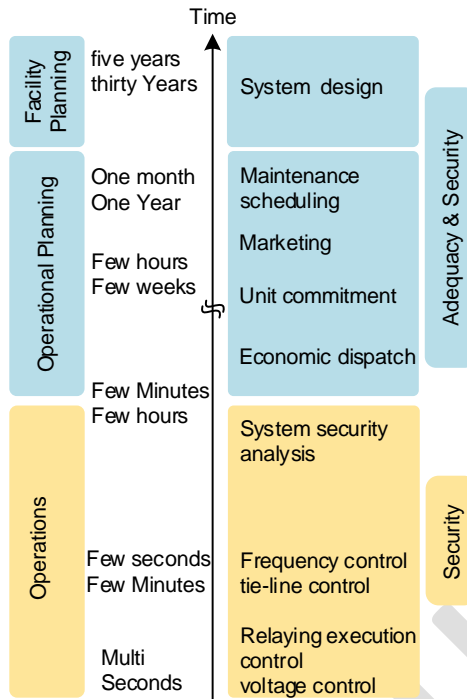


Fig. 2. Multi-time scale power system dynamics needed for power system analysis.

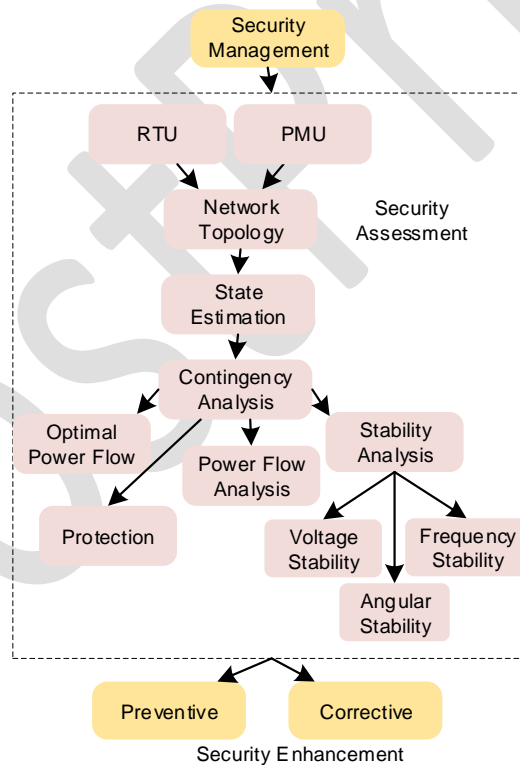


Fig. 3. Power system security assessment.

Conceptually, power system reliability is defined as the ability of a power system including physical and cyber (control) layers to supply the load with a specific level of probability [7]. It is classified into two major categories including adequacy and security. Adequacy refers to the existence of sufficient facilities to supply the consumers taking into account planned and unplanned outages. Furthermore, security is concerned with the ability of a power system to respond to any disturbances arising within the system. Generally, adequacy is associated with the planning and security is attributed to the operation. However, security is also considered during long term planning to ensure minimum level of reliability. Fig. 2 shows the different time frames and corresponding management activities attributed to the planning and operation of power systems.

A. Long-term planning

Facility planning considers the load and technology growth in order to expand and install new facilities in the next 5 to 30 years [6]. The main objectives of long-term planning are the optimal and economical expansion of power systems in order to ensure adequate and secure power delivery. The long-term trading among producers and consumers/retailers is carried out in order to overcome the future price risks.

B. Short-term planning (operational planning)

Operational planning is associated with the marketing and maintenance within the time frame of interest from a few minutes to one year. Maintenance management of facilities in order to ensure reliable power delivery is of paramount importance on power system planning. Conceptually, maintenance could be preventive or corrective. Preventive maintenance is periodically performed to decrease the probability of failure, while corrective maintenance is carried out after a failure occurrence. As a result, maintenance management can significantly affect the system availability and operational costs.

During operational planning, the electricity market includes some submarkets such as day-ahead market, intra-day market and balancing market. Producers, consumers and retailers trade each other on the day-ahead market. The energy is traded for a fixed period in the coming day, where different market players trade each other to economically supply the demand. In the intra-day market, which takes place in the hour of delivery, the market players are allowed to modify their plans considering the present state of the grid and accurate demand and generation amounts which were not much clear in the day-ahead market. Day-ahead and intra-day markets are called spot market in the literature indicating short time between planning and delivery. After scheduling the generating units, the mismatch between predicted and actual power within the operation is supplied by the balance responsible players, who are trading in the balancing market. The primary reserve immediately handles the power mismatch by the primary frequency control of generation units. Furthermore, the secondary and tertiary reserves can participate in load balancing within several minutes by trading in the real-time balance market. The post-delivery market financially settles the imbalances after real power delivery.

In the liberalized (so-called deregulated) environment, the Independent System Operator (ISO), who plays a major role in reliable operation of power system, interconnects the producers and consumers/retailers to figure out an optimal scheduling of the generation and transmission systems. This decision making refers to unit commitment, in which, the objective is to maximize the profits. Unit commitment schedules the set of generators to be on/off/standby during a period of time, usually one week, according to a forecasted load and electric grid status. The generation commitment will change hour by hour following the objectives such as profit maximization. The optimization within each hour is performed by an economic dispatch program, where the economic dispatch program obtains the optimal operating points of generating units using optimal power flow solutions.

C. Operation and control

In the operational planning phase, the ISO has been in charge of maintenance, marketing, unit commitment and economic dispatch in order to optimally schedule the generating units. The next phase is the real time operation, in which, the generators are scheduled to produce the predefined powers, primary reserve providers compensate the imbalances and then the secondary and tertiary reserves (so-called spinning reserve) suppliers compensate the imbalances due to the uncertainty of load forecast, renewable generation forecast, and unintended outages. These terms are associated with the adequacy. Moreover, in the real-time operation, the system operators concern about the system security; in particular, they need to know: how secure the system is in the present state and how secure it is going to be in the next several minutes [8]. Hence, the system security becomes the paramount issue within the operation.

Power system security refers to its ability, both at physical and control levels, to respond to any disturbances within the system [8], [9]. A secure system is able to maintain its stability, voltages and thermal limits after any disturbances. Today, the operators employ dynamic security assessment approaches to monitor the system security on-line. The building blocks of a security assessment tool is represented in Fig. 3.

At the real operation time, the system operator should know the current state of the grid. The system present state, which is the grid topology and the operating parameters such as load flow through the lines and voltage levels, should be determined by means of Supervisory Control And Data Acquisition (SCADA) system, Remote Terminal Units (RTUs) and Phasor Measurement Units (PMUs), which require a communication system [5]. These infrastructures are required in power systems for monitoring and control of such a complex system. Hence, cyber security management, bad data detection and management and estimation accuracy are of high importance for successful state estimation. The collected data are employed by state estimation block to find out the operating point of the grid by estimating all grid parameters including bus voltages and line flows.

Afterwards, the operator should do contingency analysis on the present network to figure out the consequences of the any credible outage on the system in order to ensure a certain level of security for the present operating condition as well as in the next few minutes. It requires to check both static security and dynamic security for all credible contingencies. The static security refers to the system ability to retain the steady state voltage and thermal limits (for different equipment especially for lines and transformers) in the acceptable boundaries. Hence, the power flow and optimal power flow analysis should be carried out for all the likely contingencies to check the violation of the voltages and thermal limits. Moreover, the dynamic security refers to the system ability to maintain its stability due to the contingences. Stability issues are conventionally divided into three major categories according to the instability causes. These are voltage stability, frequency stability and angular stability. Following the size of disturbance in the system, it poses the large signal or small signal instability of voltage, angle and frequency.

Moreover, the protection system should be appropriately coordinated in order to react in a suitable time to separate the faulty region/equipment. After analyzing the system security and understanding the weakest points of grid due to some contingencies, the operator should take appropriate preventive and/or corrective actions to maintain the overall system security. These actions could be re-scheduling the units, splitting the system into islands, load curtailment and so on. The operator should restore the separated or shut down regions after fault or contingency clearance.

D. Power system Concepts Classification

According to the last subsections on power system planning and operation, different power system concepts can be classified into:

- a) **Stability**: which includes different types of transient, angular, frequency and voltage stability.
- b) **Planning**: this concept includes both long term and operational planning activities such as power system expansion, electric marketing, unit commitment, economic dispatch, energy management, optimal power flow,
- c) **Protection**: protection system coordination, fault detection, short circuit analysis.
- d) **Cyber Security**: this category includes cyber-attacks, communication technologies, vulnerability and so on.
- e) **State Estimation**: state estimation methods, PMU placement, data processing
- f) **Frequency response**: primary and secondary reserve, spinning reserve
- g) **Power Flow Analysis**: different power flow analysis methods and solutions for both active and reactive powers.
- h) **New Technologies**: wind farms, PV plants, HVDC/MTDC systems, electrical vehicles.
- i) **Control**: this category consists of voltage and frequency control, hierarchical microgrid and smart grid control, distributed and decentralized control, Automatic Generation Control (AGC)
- j) **Power Quality**: includes harmonic analysis, resonance analysis, voltage sag/swell detection and control, filter design.
- k) **Reliability**: includes both adequacy and security related concepts such as adequacy and security assessment approaches, adequacy and security enhancement techniques, operational planning optimization strategies, reserve planning, maintenance scheduling, security-oriented planning and so on.
- l) **Restoration and outage**: power system restoration, failure/ outage identification, splitting.

III. STANDARD TEST SYSTEMS

Table I. Overview on standard test systems.

Test System	Voltage (kV)	AC/DC	No. of Buses	No. of Generators	Load (MW, MVAR)	Most common application	Time of interest for most common used application
IEEE 9	13.8, 16.5, 18, 230	AC	9	3	315, 115	Stability	Milli to several seconds
IEEE 14	13.8, 18, 69	AC	14	5	259, 73.5	State Estimation	-
IEEE 30	33, 132	AC	30	6	283.4, 126.2	Planning	A few hours to several years
IEEE 39	345	AC	39	10	6097, 1409	Stability	Milli to several seconds
IEEE 57	138, 345	AC	57	7	1251, 336.4	State Estimation	-
IEEE 118	138, 345	AC	118	19	3668, 1438	Planning	A few hours to several years
IEEE 300	138, 230, 345	AC	300	69		State Estimation	-
IEEE RTS-24	230, 138	AC	24	32	3405, -	Reliability	Several minutes to several years
RBTS	230	AC	6	11	240, -	Reliability	Several minutes to several years
CIGRE B4 DC	±400, ±200, 380,145	DC	Fig. 20	Fig. 20	7500, -	New Technologies	Milli seconds to minutes
CIGRE MV	20	AC	14	utility	~43, ~16	Control	Milli seconds to seconds
CIGRE LV	0.4	AC	Fig. 21	utility		New Technologies	Milli seconds to minutes
CIGRE 32	130, 220, 400	AC-DC	74	20	11060, -	Control	Milli seconds to seconds
CIGRE HVDC	345, 230	DC	2	2-utility	1000 (base)	Stability/Control	Milli seconds to seconds

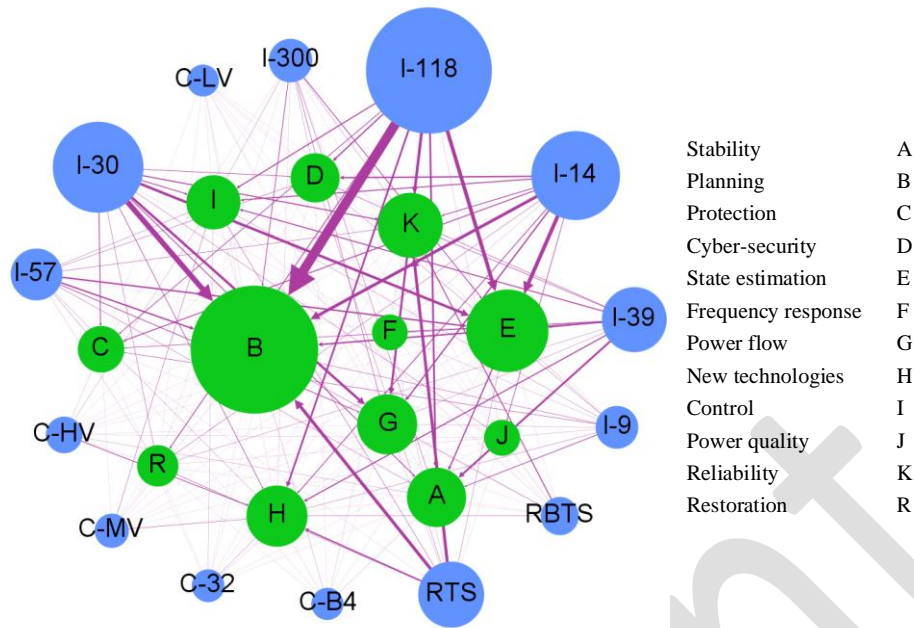


Fig. 4. Overview of electrical test systems and applications; blue: test systems, green: applications – I-: IEEE, C-: CIGRE.

Two major test systems are covered in this study including IEEE and CIGRE benchmarks. The general specifications of the standard test systems are summarized in Table I and the corresponding single-line diagrams are shown in the Appendix. All of the IEEE benchmarks are suitable for conventional AC power systems. Meanwhile, the CIGRE benchmarks, which are indeed a part of European countries grids, include AC and/or DC power systems. Fig. 4 shows the statistical analysis on the reviewing 2,500 papers at different power system concepts. According to this figure, planning followed by state estimation are the most published articles in power systems. Furthermore, the IEEE 118 Bus followed by the IEEE 30 and 14 Bus benchmarks are the most commonly used benchmarks for power system studies. The distribution of applicability of each test system for different topics is shown in Fig. 5.

IEEE 9 Bus: This test system is a modified version of Western System Coordinated Council (WSCC) 9 Bus test case, which is a well-known test system for transient stability analysis [10]. As shown in Fig. 5(a), this test case has been employed for stability studies in 23% of reviewed papers. It has been widely used for protection studies in power systems as well.

IEEE 14 Bus: This test system is a simplified model of the American Electric Power System in the Midwestern US as it was in 1962. This test system is mostly used for state estimation in 24% and planning studies in 20% as it is shown in Fig. 5(b).

IEEE 30 Bus: This test system is a part of American Electric Grid as it was in 1961. It has been mostly used for planning studies in 34% and then for state estimation purposes in 16% of the total studies as shown in Fig. 5(c).

IEEE 39 Bus: This is the well-known New England 10 generator power system. This test system has been widely used for small signal stability in conventional power systems [11]. The result of present overview shows that this system has been used for stability studies in 21% of the reviewed papers. It has also been used for planning studies (16%) and new technology application (12%) as shown in Fig. 5(d).

IEEE 57 Bus: This system is a part of American Electric Grid as it was in 1960. It has been mostly used for planning studies and for state estimation purposes in 25% of total cases as shown in Fig. 5(e).

IEEE 118 Bus: This test system is a part of American Electric Grid as it was in 1962. Fig. 5(f) shows the usage of this test system for different studies, where it mostly has been employed (in 38%) for planning studies.

IEEE 300 Bus: This test system was developed by the IEEE Test Systems Task Force in 1993. Following Fig. 5(g), this system has mostly been employed for state estimation and planning studies.

IEEE RTS-24 Bus: This test system is the IEEE Reliability Test System (RTS) – the first version known as RTS-79, the second version known as RTS-86 – including 24 busses are the well-known standard test system for reliability studies [12], [13]. Fig. 5(h) shows that this system is widely used for planning (34%) and reliability analysis (31%). For inter-area analysis, three or five RTS test systems as stated in RTS-96 can be connected together to construct a larger power system [14]. A recent update on RTS-96 has been presented by U.S. Department of Energy’s Grid Modernization Laboratory Consortium (GMLC), which is called RTS-GMLC [15]. This update includes replacing coal and oil fueled generations with natural gas generations, integrating solar and wind generations, updating load profiles as well as

modifications on generators characteristics, line limits and so on. The presented update is based on the real-world power system data. This update will introduce unique opportunities to explore the operational and planning issues in modern power systems [15].

RBTS: This is a well-known test system for reliability studies proposed by Prof. Roy Billinton, designated as Roy Billinton Test System (RBTS) [16]–[18], for education and research purposes. As shown in Fig. 5(i), this system has widely (52%) been used for reliability studies. Moreover, due to the size of this system, it has been used for a wide range of reliability studies associated with planning, operation and inclusion of new technologies in the power networks.

CIGRE B4 DC: This test system has been developed by Cigre B4 working group for DC system studies. The test case includes two onshore AC systems, four offshore AC systems, two DC nodes with no connection to AC systems, and three interconnected DC systems called DCS1, DCS2 and DCS3 [19]. DCS1 is a two-terminal symmetric monopole HVDC link with ± 200 kV. DCS2 is a four-terminal symmetric monopole HVDC link with ± 200 kV, and DCS3 is a five-terminal bi-pole HVDC meshed grid with ± 400 kV. Each test system can be separately used for power system studies where the whole system is complex. The detailed system specifications and parameters are available in [19]. This test system has been cited in a few works in the target journal publications for power flow analysis and control of HVDC systems.

CIGRE MV: This benchmark is a European test system for integration of renewable resources in Medium Voltage (MV) 20 kV distribution systems [20]. The American version is also available in [20]. The test system has been proposed by CIGRE Working Group WG C6-04 for distributed resources and storage coordinated control, energy management, protection and fault ride through testing, islanded operation, power flow analysis and so on [20], [21]. An example of integrating renewable resources into the MV distribution grid is provided in [21].

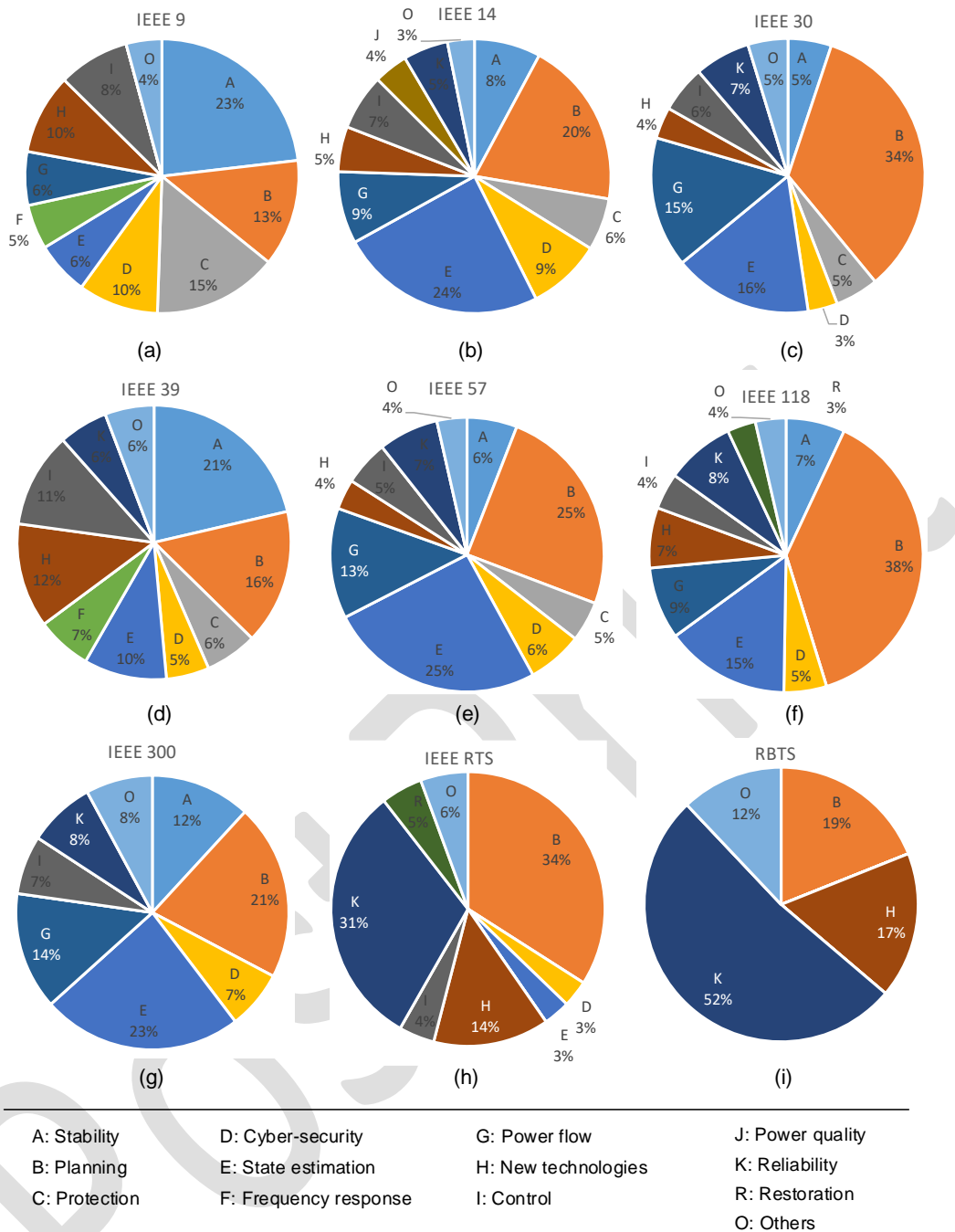


Fig. 5. Applicability of test systems in different power system analysis; (a) IEEE 9 Bus, (b) IEEE 14 Bus, (c) IEEE 30 Bus, (d) IEEE 39 Bus, (e) IEEE 57 Bus, (f) IEEE 118 Bus, (g) IEEE 300 Bus, (h) IEEE RTS (24 Bus), and (i) RBTS.

CIGRE LV: This European test system includes three 0.4 kV distribution feeders for commercial, residential and industrial consumptions [20], [21]. This network has also been proposed by CIGRE Working Group WG C6-04 for integrating renewable resources to Low Voltage (LV) distribution systems. An example of integrating renewable resources to LV distribution grid is provided in [21].

CIGRE (Nordic) 32: This test system is driven from the Swedish and Nordic power grids and it has been developed for voltage security analysis under IEEE Task Force PES-TR-19 [22]. In the modified version of this test system, DC transmission lines are also considered.

CIGRE HVDC: This is the first CIGRE HVDC test system developed in 1985. This test system is a monopole with ± 500 kV and 12-pulse rectifier and inverters connected to two AC grids [23]. This benchmark has been used for control of HVDC systems.

IV. APPLICATION OF TEST SYSTEMS

Fig. 6 shows the distribution of using test systems for specific applications as described in the following:

Stability: For stability analyses, the IEEE 39 Bus system has been utilized in 26% of case studies as shown in Fig. 6(a). Afterwards, the IEEE 188 Bus and IEEE 14 Bus systems have been used respectively in 23% and 16% of the total case studies. Moreover, the IEEE 39 Bus test system has mostly been used for transient stability analysis in 46% of cases, while the IEEE 118 Bus benchmark has been used for voltage stability analysis in 54% of the reviewed papers as shown in Fig. 7.

Protection: Fig. 6(b) shows the distribution of test systems used for protection purposes. The IEEE 14, 30, 118 Bus test systems are the most used test cases with the distribution of 23%, 20% and 17% of the whole papers reviewed on the protection studies.

Frequency response: The IEEE 39 Bus test system has mostly been employed (almost in half of the total cases) for frequency studies in power systems as shown in Fig. 6(c). It is worth mentioning that this test system includes comprehensive data for the generators in order to appropriately model and analyze the frequency response of systems.

Reliability: Fig. 6(d) shows that the IEEE-RTS has been employed for reliability studies in 32% of the total cases. Furthermore, the IEEE 118 Bus test system is the second common used test system with the frequency of 23%. This figure shows that the RBTS has used for reliability studies in 11% of case studies used for reliability assessment. Moreover, Fig. 8 shows that the IEEE-RTS has been used for adequacy studies in 78% while for the security analyses the IEEE 118 Bus test system has been employed in 94% of the reviewed case studies.

Power Flow: The IEEE 30 and 118 Bus systems have been employed in 32% and 28% of the total cases for power flow studies as shown in Fig. 6(e).

Control: The IEEE 118, 14, 39 and 30 Bus systems have mostly been employed for the studies associated with power systems control as shown in Fig. 6(f).

Cyber security: The IEEE 14 and 118 Bus systems have been employed in 28% and 27% of the total cases for cyber security studies as shown in Fig. 6(g).

Power Quality: Fig. 6(h) shows that the IEEE 14 and IEEE 30 Bus test systems have been used for power quality analysis with the frequency of 47% and 25% of the total cases.

Restoration: For restoration studies, the IEEE 118 Bus test system is the mostly used system with the frequency of 31% as shown in Fig. 6(i).

State estimation: As shown in Fig. 6(j), the IEEE 14, 118 and 30 Bus test systems have been mostly used for state estimation studies in power systems.

Planning: The IEEE 118 and 30 Bus benchmarks have been employed in 38% and 21% of the total cases for planning studies as shown in Fig. 6(k). The reason of this high usage of the IEEE 118 bus test system for planning studies is that it is a large system and has the capability to divide it into two, three or four areas. Hence, it could be an appropriate case for interarea studies.

New technologies: For this category, as shown in Fig. 6(l), the IEEE 118, RTS, 39, and 14 Bus test systems have been widely used. However, these test systems have been modified by the researchers to include the new technologies such as DC transmission systems, wind farms, PV plants, electric vehicles and so on. Therefore, there is not a single test system for including new technologies in power system studies. Meanwhile, some authors have modified the test systems by adding extra sections to the existing benchmark, while others have preferred to replace some parts with the new technologies. The DC based test systems such as CIGRE B4 DC have not been widely used for power system studies in the reviewed papers.

The data availability of different test systems is summarized in Table II. The original data has been developed for the specific applications. However, for the other studies, the standard test systems specifications have been modified. For instance, the IEEE 118 Bus test system is modified for security assessment, and IEEE 14 Bus test system is used for power quality analysis by implementing non-linear loads and power filters.

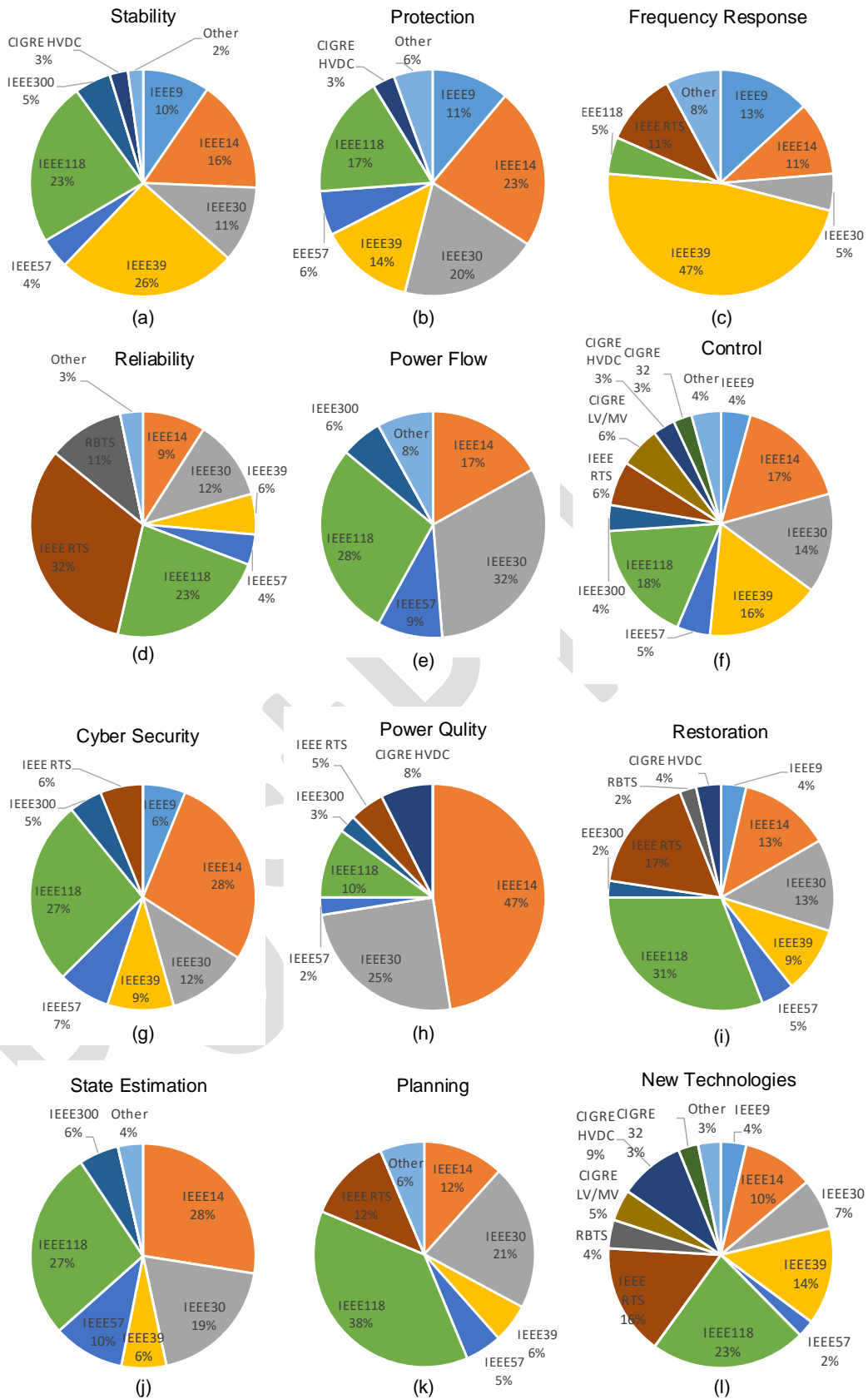


Fig. 6. Usage of standard test systems for power system studies (a) stability, (b) protection, (c) frequency response, (d) reliability, (e) power flow, (f) control, (g) cyber security, (h) power quality, (i) restoration, (j) state estimation, (k) planning, and (l) new technologies.

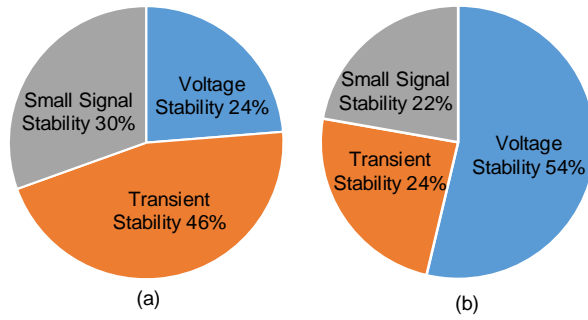


Fig. 7. Usage of (a) IEEE 39 Bus test system and (b) IEEE 118 Bus test system for stability studies.

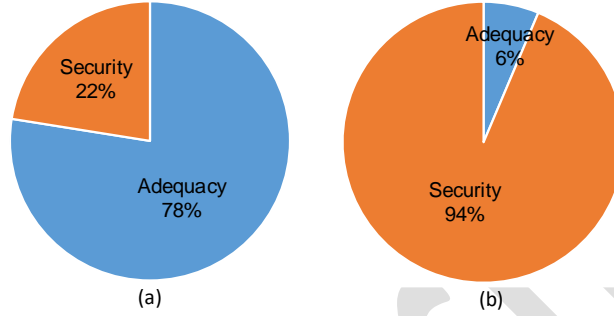


Fig. 8. Usage of (a) IEEE RTS test system and (b) IEEE 118 Bus test system for reliability studies.

Table II. Availability of data.

Test System	Voltage stability	Angular stability	Planning	State estimation	Power flow	Reliability: adequacy	Control
IEEE 9			X	X	X		
IEEE 14			X	X	X		
IEEE 30			X	X	X		
IEEE 39		X	X	X	X		X
IEEE 57			X	X	X		
IEEE 118			X	X	X		
IEEE 300			X	X	X		
IEEE RTS-24			X	X	X	X	
RBTS			X	X	X	X	
CIGRE B4 DC			X	X	X		X
CIGRE MV			X	X	X		X
CIGRE LV			X	X	X		X
CIGRE 32	X		X	X	X		
CIGRE HVDC			X	X	X		X

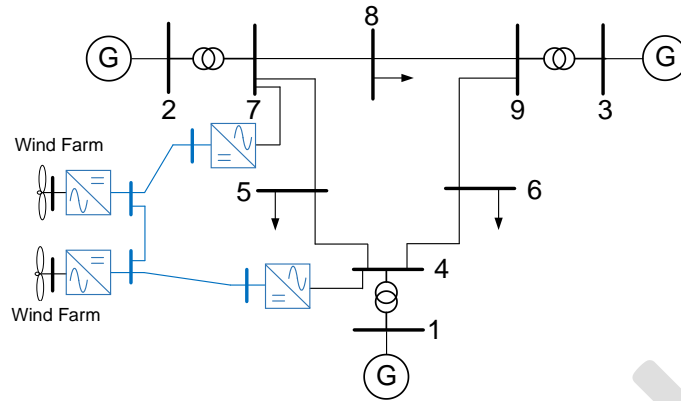


Fig. 9. IEEE 9 Bus test system with DC grid [24].

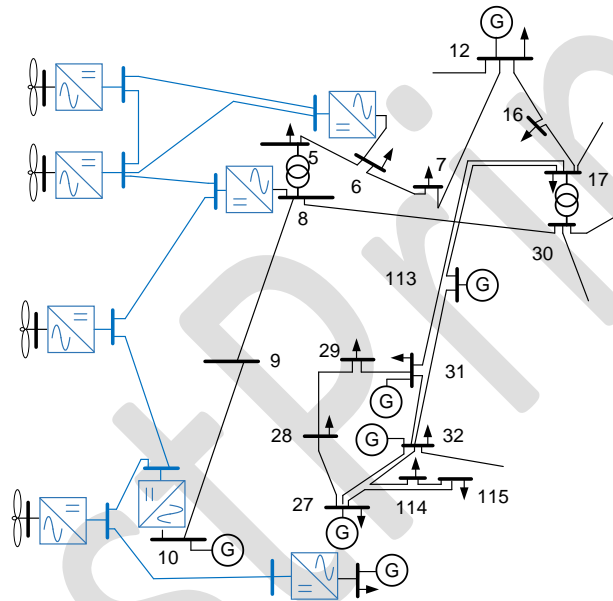


Fig. 10. IEEE 118 Bus test system with DC grid [24].

V. PROS AND CONS OF EXISTING TEST SYSTEMS

IEEE Test systems are widely used for different power system studies, while they have not been updated to include variable energy resources and new technologies such as electronic transmission and distribution systems. Even though some modifications have been presented on the existing test systems, for instance the ones shown in Fig. 9 and Fig. 10 [24], they are not adopted from the real-world power systems. As a result, the employed data for the modern part with the conventional data for the existing network may cause erroneous consequences.

Furthermore, the dedicated efforts on updating the IEEE RTS-96, called RTS-GMLC [15], make it feasible for modern power system studies, while more upgrades should be performed in the next versions. This is due to the fact that it does not cover the detail information of wind turbines, wind farms, solar power plants, and energy storages. It is more applicable for planning studies such as unit commitment, economic dispatch, energy management and adequacy assessment. Meanwhile, in the presented update of RTS-GMLC, the reliability data for variable energy resources have not been provided especially for power electronic based technologies. However, these technologies are one of the frequent failure sources in wind farms [25]. On the other hand, the structure of a wind farm can affect its reliability. Thereby, more detailed technical information regarding wind farms and solar power plants should be provided in the next updates. This test system, neither RTS-96 nor RTS-GMLC is not flexible for microgrid analysis including operational planning, operation and control.

Moreover, the IEEE test systems employed for stability analysis are not appropriate for control-related stability issues such as harmonic stability [26]. Even the IEEE 39 Bus system, which has especially presented for stability analysis, requires appropriate modifications in order to include the new technologies.

The Cigre benchmarks are more suitable for modern power system studies in which they comprise of new technologies. The Cigre B4 DC can be used for stability, protection, power flow, planning, control power quality and frequency response analyses in multi-terminal DC grids. However, it is not applicable for reliability-oriented analysis such as adequacy assessment due to the lack of reliability data. Moreover, the wind farm structures have not been covered in this benchmark. The Cigre LV/MV grids are suitable for AC microgrid studies such as control and planning. However, they need some modifications for reliability and cyber-security analysis. The Cigre 32 Nordic test system requires to be updated considering the variable energy resources and DC transmission systems.

VI. MODERN TEST SYSTEMS CHALLENGES AND REQUIREMENTS

The paradigm shift from the centralized, top-down strategy to the distributed, bottom-up one in power flow direction and control systems is revolutionizing the structure of power systems [1]. Decarbonization and economization have intensified the increasing use of renewable resources and energy storages in order to form self-organizing scalable, clean, reliable, resilient and efficient power systems. This can be achievable by employing the microgrid and smart-grid technologies for reliable and efficient operation of different energy resources in a distributed manner. The microgrids will be the segments of the future power systems which can be operated in the either grid-connected or islanded modes. The control, monitoring and coordination of clusters of microgrids require smarter solutions relying on communication systems and/or decentralized approaches. Moreover, thanks to power electronic advances, the DC systems invented by Edison are re-competing with the AC systems in transmission and distribution system levels. It has introduced more flexibility and controllability to electric power transmission and distribution with efficient and cost-effective solutions. Thereby, the modern power systems are going to be equipped with new technologies such as DC high voltage transmission and medium voltage distribution systems, distributed generations in low voltage and medium voltage levels, interconnected AC/DC microgrids, large scale wind and PV power plants, large scale energy storages, electric vehicles and so on. All the new technologies rely on power electronic converters for energy conversion.

Increasing use of power electronic converters in different levels in power systems pose new challenges to the power system reliability and security. Power converters are one of the failure sources in photovoltaic and wind power systems [25], [27]–[29], where the environmental and/or operational conditions may trigger some failure mechanisms [30]. Furthermore, the mutual interactions among different energy sources can affect the converters loading and consequently their reliability [31]. Thereby, in terms of reliability, system-level analysis is required in order to reliably design, control and operate the power converters for different applications [30]. This can be feasible if more realistic power electronic based test systems are prepared. In this regard, suitable test systems must be developed for AC and DC microgrid applications, wind farm and photovoltaic plant structures, MVDC distribution systems and so on.

Moreover, proliferation of power electronic converters in power systems may pose security issues to operation of future power systems. For instance, interactions among converter control systems, and converters control with the power system may cause control-related stability issues from a few hertz to several kilo hertz [26], [32]. Therefore, suitable test systems are required for control-related stability studies in modern power systems. A proper test system should cover complete model of power converters and the corresponding control systems in order to illustrate a certain instability phenomenon associated with the interaction between the converter and its control with the system.

The cluster of hybrid AC/DC microgrids in low and medium voltage distribution systems will be the structure of future power systems providing an efficient and reliable infrastructure for developing smarter grids. Planning, control, monitoring and operation of cluster of microgrids are of high importance for reliable and efficient power delivery in modern smart grids. The bidirectional top-down and bottom-up power flow between transmission and distribution systems introduces more planning and operation challenges. This requires communication systems in order to facilitate the reliable operation of such grids. However, it poses cyber-security issues to the modern power systems. All these issues must be explored using appropriate interconnected transmission-distribution test systems.

On the other hand, for reliability studies, especially for the case of considering renewable generation connected to the conventional power systems, a compatible set of reliability data for both conventional and modern systems should be employed. The conventional reliability test cases such as the IEEE-RTS and RBTS require to be modified

considering the new technologies. The technical information regarding the structure of wind farms and photovoltaic plants, and their reliability data should be provided in the updated version of reliability test systems. Furthermore, these test systems should be extended to medium and low voltage levels with appropriate inclusion of AC/DC microgrids.

As a result, the following recommendations are proposed for upgrading the test systems for modern power system analysis:

- 1- The test systems should include structure of wind farms and photovoltaic plants, and appropriate reliability data for planning and operation studies.
- 2- The low and medium voltage (both AC and DC) distribution systems should be interconnected to the high voltage bulk system for microgrid and smart grid related studies.
- 3- Smart grid technologies, such as communication systems and smart meters, should be provided in the test benchmark for control, monitoring, operational planning and cyber-security studies.
- 4- Power converters and their controls for HVDC and MVDC transmission systems, wind turbines and photovoltaic plants should be provided in the test system. The operation of converters in grid forming, following, supporting, and maximum power tracking mode can affect the system performance.
- 5- Besides the large test systems for simulation studies, a scaled-down benchmark is of high importance for experimentally evaluating the effectiveness of some solutions in different power system analysis categories. Moreover, some power system phenomena solely happen in high voltage level, the low voltage implementation may not be suitable for exploring those problems. However, due to the security issues, examination of solutions in real-world system is not possible. In this case, the test systems may be implemented in Real Time Digital Simulator (RTDS) environment and some parts of system under study can be physically implemented.
- 6- Since power electronic reliability is becoming an important issue, the device-level analysis requires to be carried out with real-world tests. However, the reliability and lifetime of power devices depend on the operation condition which is related to the system-level controls in power systems. Therefore, real-world analysis of such kind of issues can be performed by implementing the part of converter in RTDS environment especially for the high-power multi-level converters, where testing the whole converter is not cost-effective.

VII. CONCLUSION

This paper reviews the standard test systems including IEEE and CIGRE benchmarks and their applicability for power system studies. The ultimate goal of power system studies is to supply the end users economically and with an acceptable level of reliability. Achieving such a goal for a large and complex system requires long-term studies for design and planning, and short-term studies for operational planning as well as real-time operation. Generally, the long-term and operational planning relate to the decision makings associated with the system adequacy, while security becomes significant for the short-term operation decision makings. Beyond the general concepts of the reliability studies, adequacy and security assessment require detailed analysis including stability, power flow, state estimation, protection, control and so on. These analyses require an appropriate test system to illustrate and evaluate the desired concepts. This paper has identified almost 2,500 relevant journals of the IEEE to find out the applicability of the existing test systems for different concepts of power system studies. This study shows that the most efforts have focused on planning of power systems and the most popular test system for power system studies is the IEEE 118 Bus benchmark.

This study shows the lack of standard test systems for new technologies such as wind farms, photovoltaic systems, HVDC-MVDC systems and electric vehicles. The IEEE 118 Bus, IEEE-RTS and IEEE 39 Bus have been modified for different studies on the new technologies. However, these systems are not suitably designed for exploring different concepts of power system studies. Therefore, by growing the proliferation of the new technologies, developing relevant benchmarks becomes a must. This paper presents some recommendations for upgrading the benchmarks for modern power system analysis.

VIII. APPENDIX

The single line diagram of the standard grid topologies is shown in the following. More detailed data regarding each system is available in the corresponding references.

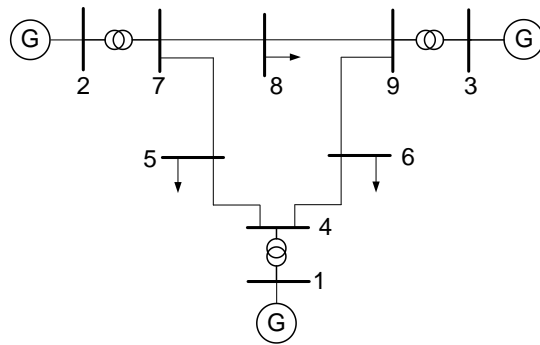


Fig. 11. IEEE 9 Bus test system [33]–[36].

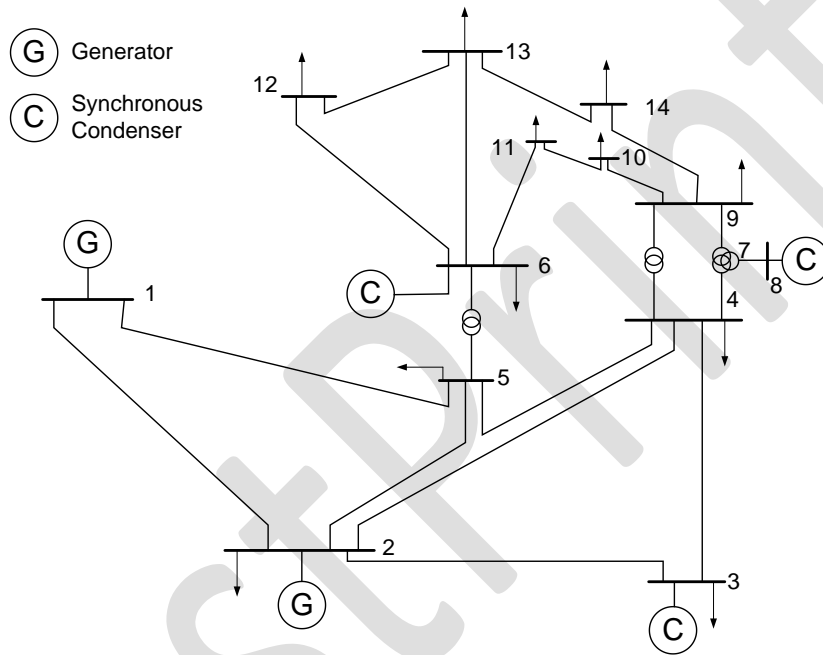


Fig. 12. IEEE 14 Bus test system [33]–[36].

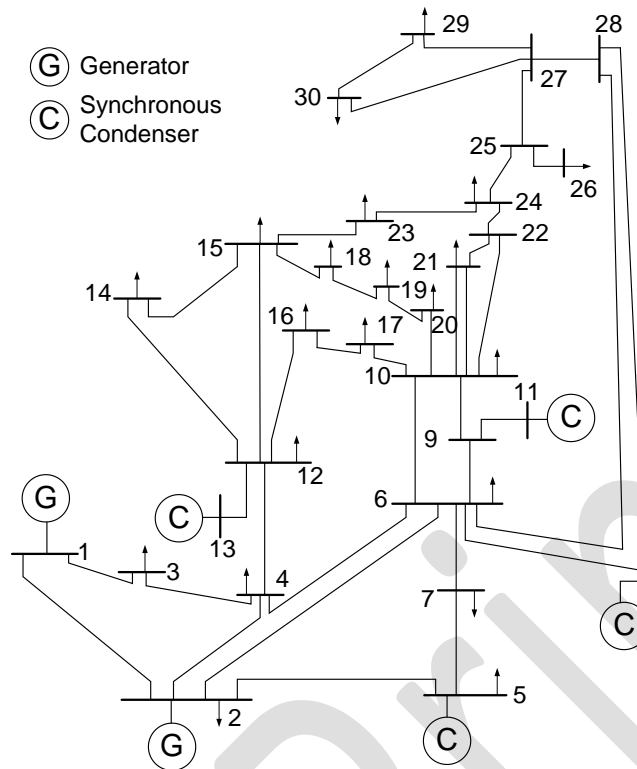


Fig. 13. IEEE 30 Bus test system [33]–[36].

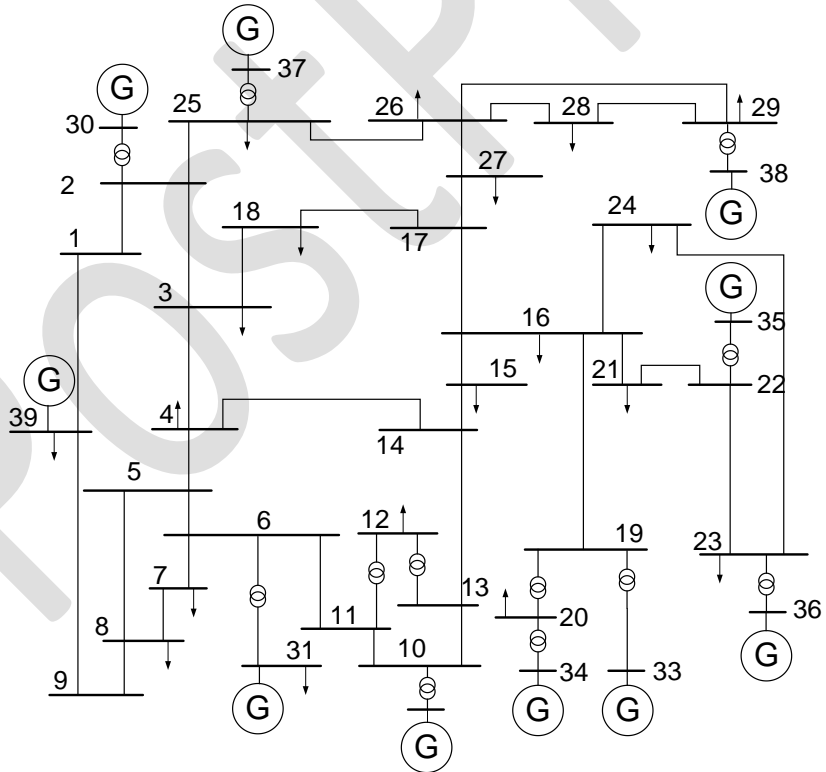


Fig. 14. IEEE 39 Bus test system [11], [33]–[36].

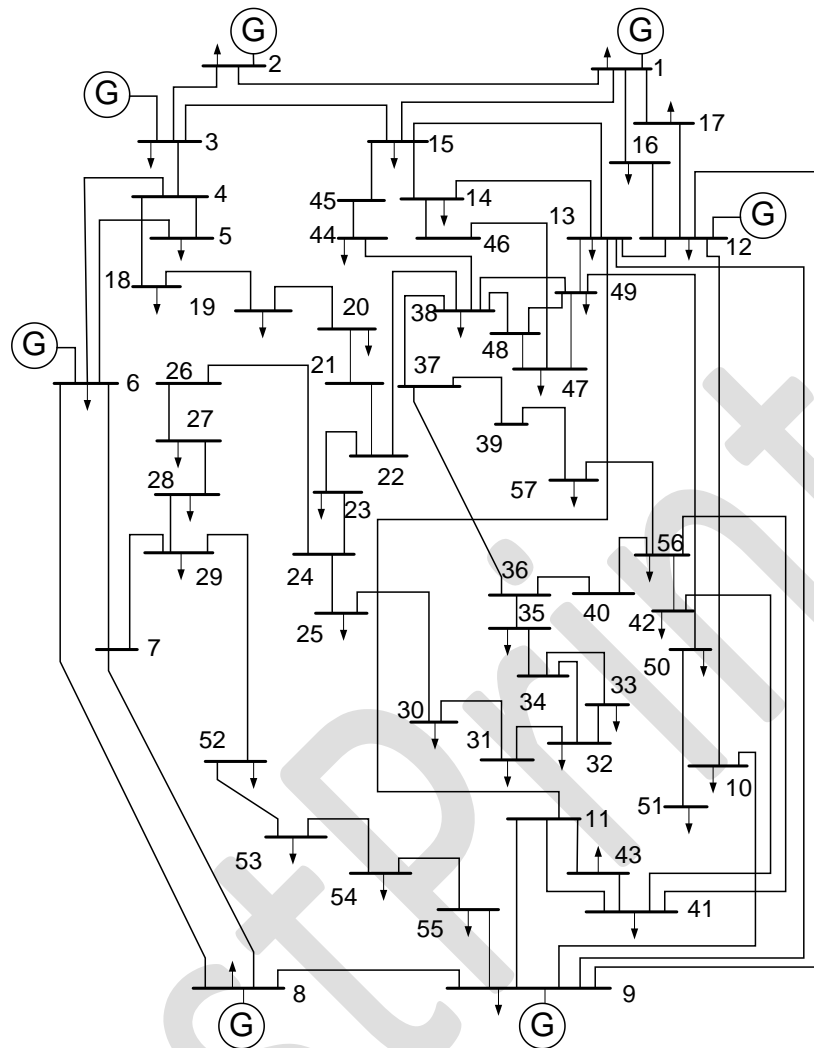


Fig. 15. IEEE 57 Bus test system [33]–[36].

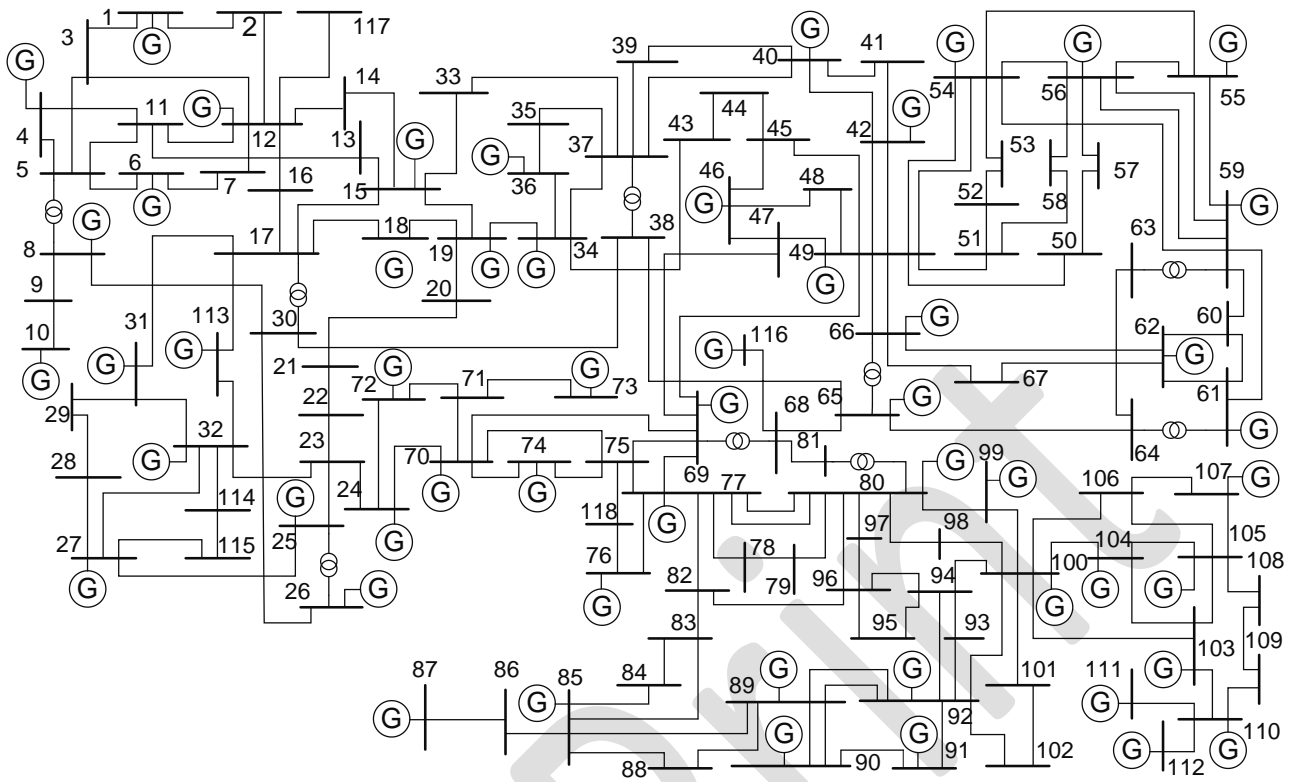


Fig. 16. IEEE 118 Bus test system [33]–[36].

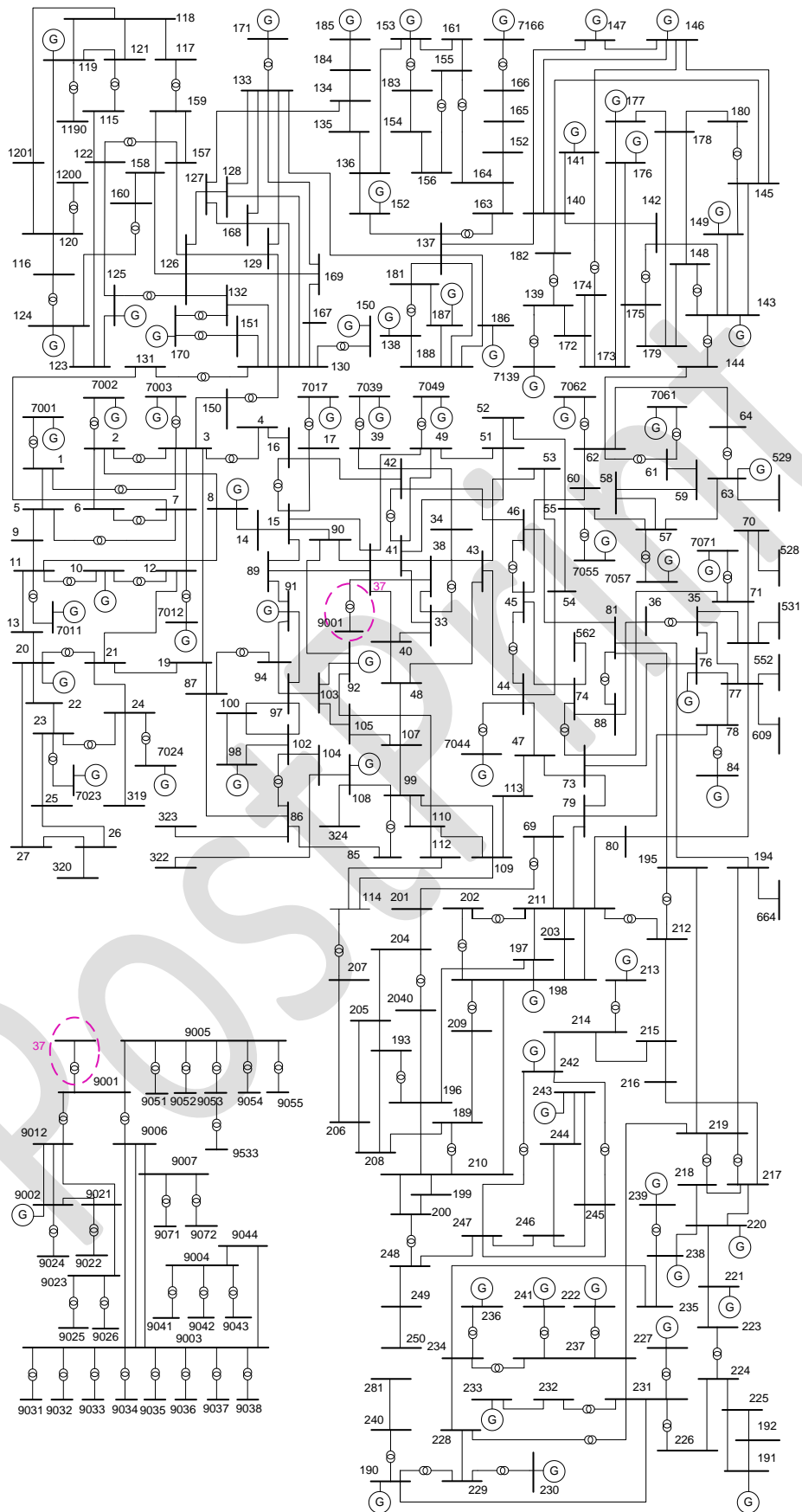


Fig. 17. IEEE 300 Bus test system [33]–[36].

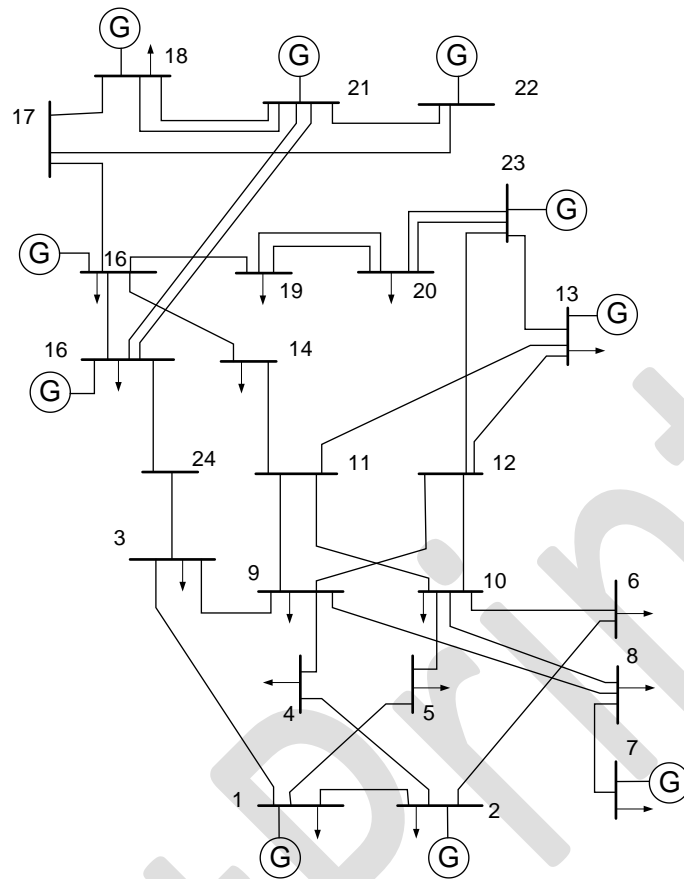


Fig. 18. IEEE RTS - 24 Bus test system [12]–[14], [33]–[36].

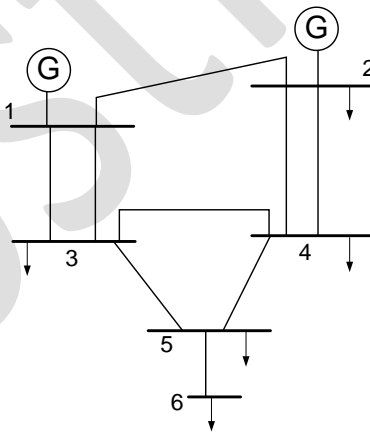


Fig. 19. RBTS 6 Bus test system [16]–[18].

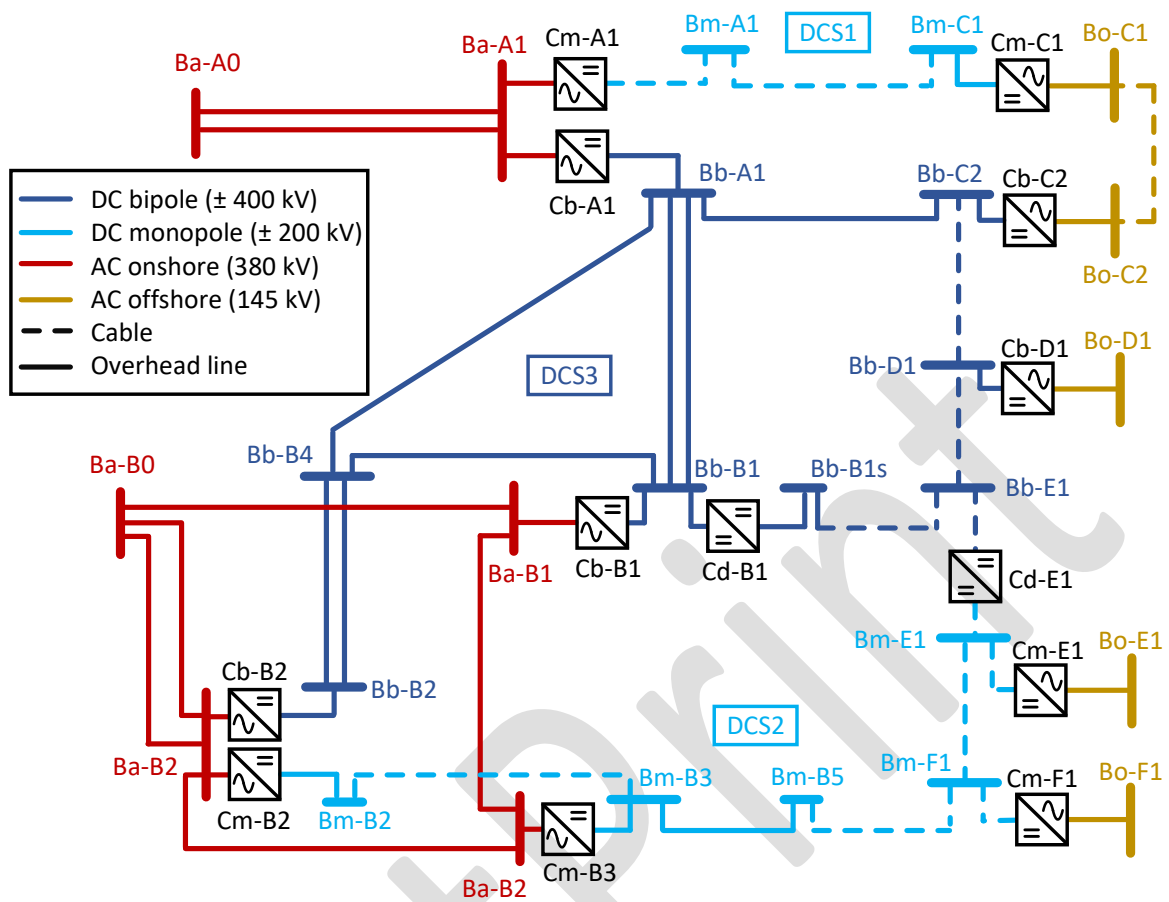


Fig. 20. CIGRE B4 DC test system [19].

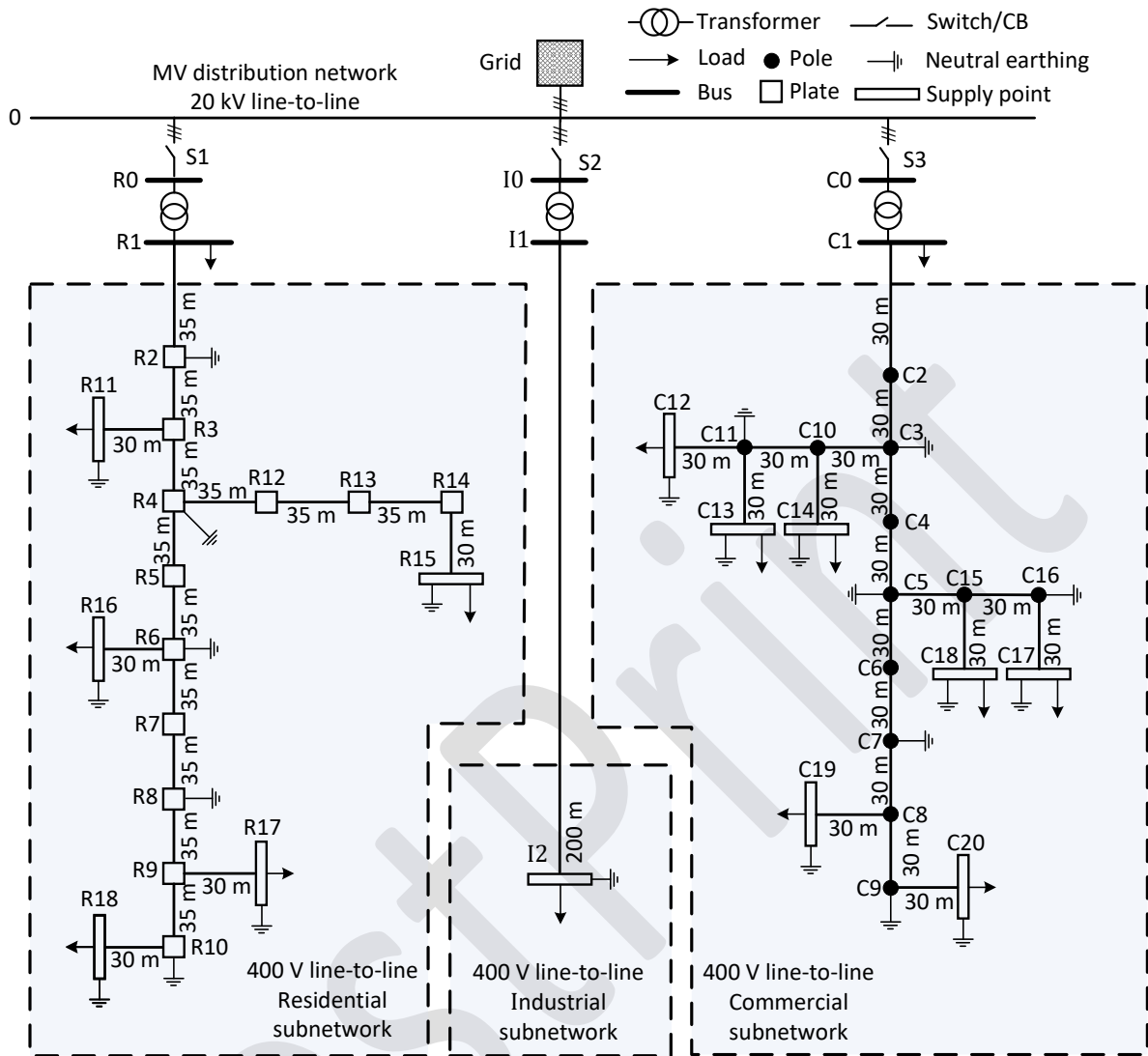


Fig. 21. CIGRE LV test system [20], [21].

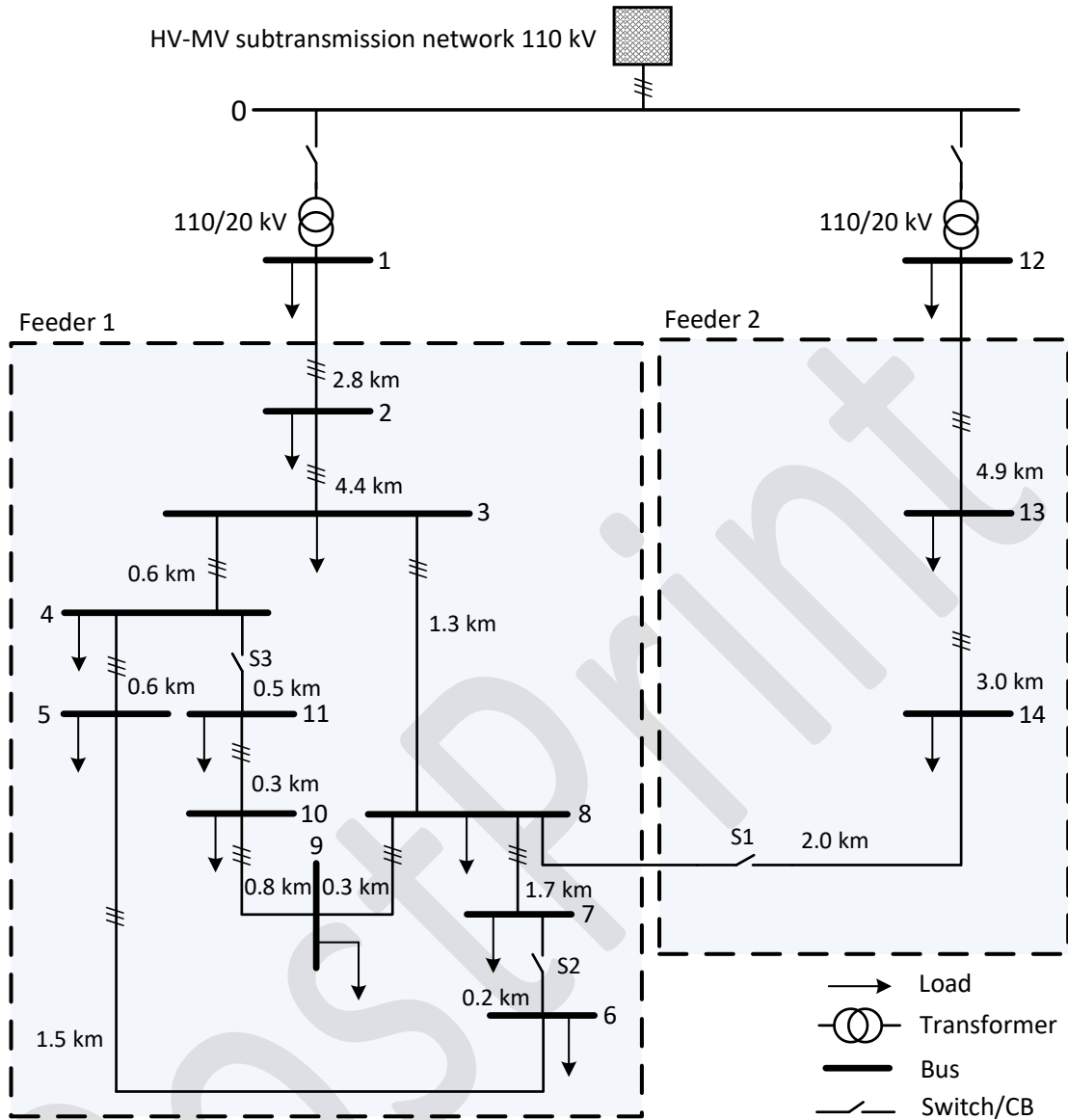


Fig. 22. CIGRE MV/LV test system [20], [21].

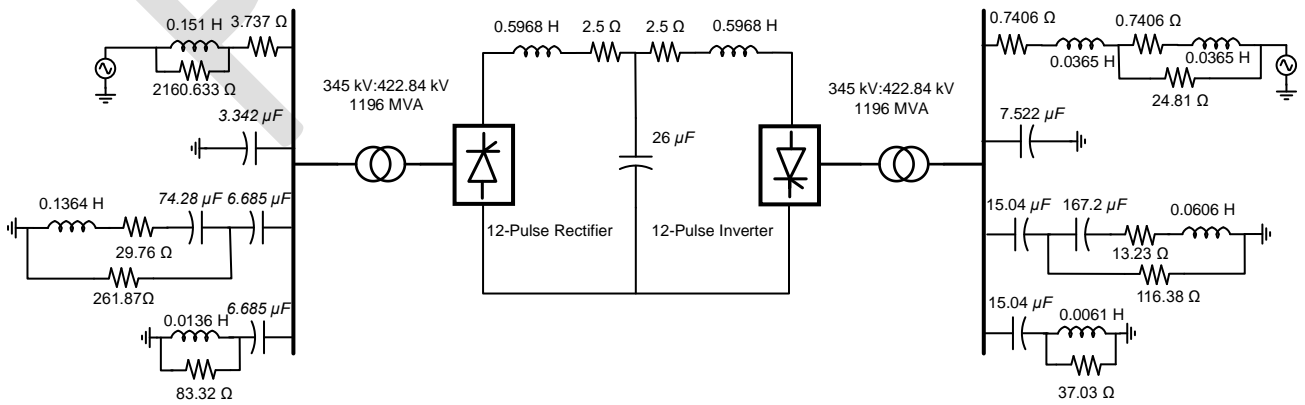


Fig. 23. CIGRE HVDC test system.

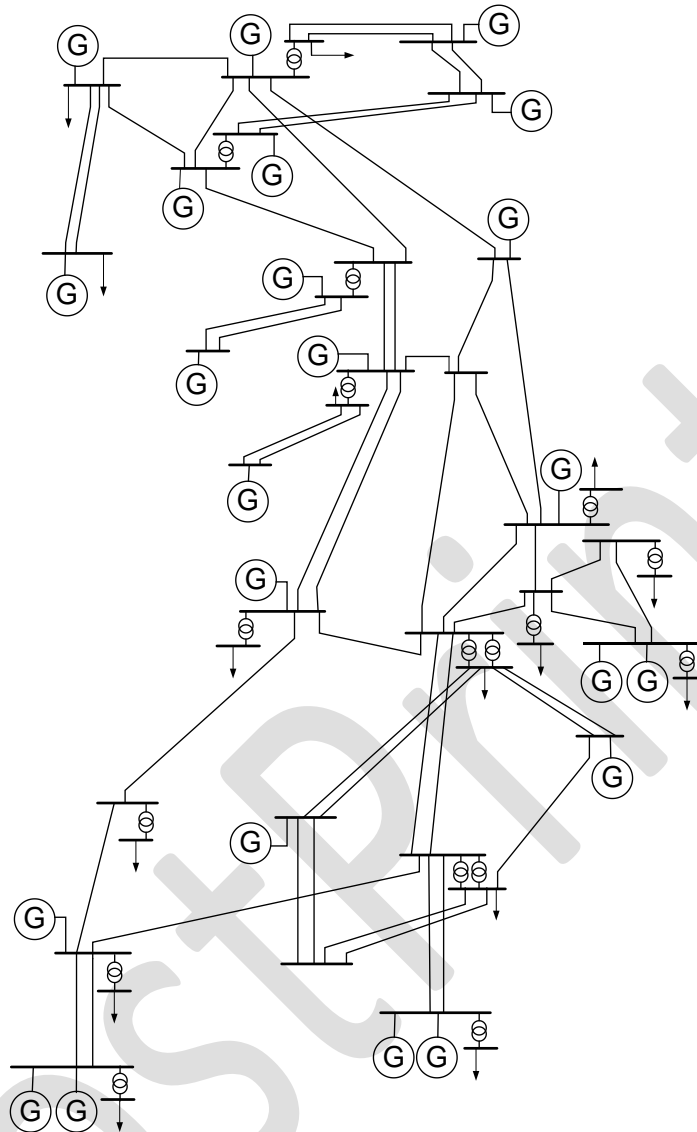


Fig. 24. CIGRE 32 (Nordic) test system [22].

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REFERENCES

- [1] F. Blaabjerg, Y. Yang, D. Yang, and X. Wang, "Distributed Power-Generation Systems and Protection," *Proc. IEEE*, vol. 105, no. 7, pp. 1311–1331, Jul. 2017.
- [2] H. E. Johan, G. W. Steven, and H. Ramtin, "Third EGrid Workshop Maps the Grid of the Future: Attendees Engage to Examine the Role of Power Electronic Applications in Modern Electric Power Systems," *IEEE Power Electron. Mag.*, vol. 6, no. 1, pp. 48–55, 2019.
- [3] Z. Cheng, J. Duan, and M. Y. Chow, "To Centralize or to Distribute: That Is the Question: A Comparison of Advanced Microgrid Management Systems," *IEEE Ind. Electron. Mag.*, vol. 12, no. 1, pp. 6–24, 2018.
- [4] L. Bertling, P. Bangalore, and L. A. Tuan, "On the Use of Reliability Test Systems: A Literature Survey," *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–9, 2011.
- [5] L. L. Grigsby, Ed., "*POWER SYSTEM STABILITY and CONTROL.*" Taylor & Francis Group, LLC, 2007.

- [6] G. B. Sheblé, "Power System Planning (Reliability)." Bosa Roca, United States: Taylor & Francis Inc, 2001.
- [7] R. Billinton and R. N. Allan, "Reliability Evaluation of Power Systems," Second Edi., vol. 30, no. 6. Plenum Press, 1984.
- [8] K. Morison, L. Wang, and P. Kundur, "Power System Security Assessment," *IEEE Power Energy Mag.*, vol. 2, no. october, pp. 30–39, 2004.
- [9] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziaargyriou, D. Hill, A. Stankovic, C. Taylor, and V. Cutsem, "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 1387–1401, 2004.
- [10] A. Delavari, I. Kamwa, and P. B. Canadian, "Simscape Power Systems Benchmarks for Education and Research in Power Grid Dynamics and Control," in *Proc. IEEE CCECE*, 2018, pp. 1–5.
- [11] IEEE PES Technical Report TR18, "Benchmark Systems for Small-Signal Stability Analysis and Control," *IEEE Power Energy Soc.*, pp. 1–390, 2015.
- [12] IEEE RTS Task Force of APM Subcommittee, "IEEE Reliability Test System," *IEEE Trans. Power Appar. Syst.*, vol. PAS-98, no. 6, pp. 2047–2054, Nov. 1979.
- [13] R. N. Allan, R. Billinton, and N. M. K. Abdel-Gawad, "The IEEE Reliability Test System - Extensions to and Evaluation of the Generating System," *IEEE Trans. Power Syst.*, vol. 1, no. 4, pp. 1–7, 1986.
- [14] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The IEEE Reliability Test System-1996. A Report Prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1010–1020, 1999.
- [15] C. Barrows, A. Bloom, A. Ehlen, J. Ikäheimo, D. Krishnamurthy, J. Lau, M. O. Connell, E. Preston, S. L. Member, A. Staid, S. Member, and J. Watson, "The IEEE Reliability Test System : A Proposed 2019 Update," *IEEE Trans. Power Syst.*, no. DOI 10.1109/TPWRS.2019.2925557, pp. 1–9, 2019.
- [16] R. Billinton, S. Kumar, N. Chowdhury, K. Chu, K. Debnath, L. Goel, E. Khan, P. Kos, G. Nourbakhsh, and J. Oteng-Adjei, "A Reliability Test System for Educational Purposes-Basic Data," *IEEE Power Eng. Rev.*, vol. 9, no. 8, pp. 67–68, 1989.
- [17] R. N. Allan, R. Billinton, I. Sjarief, L. Goel, and K. S. So, "A Reliability Test System for Educational Purposes-Basic Distribution System Data and Results," *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 813–820, 1991.
- [18] R. Billinton, S. Kumar, N. Chowdhury, K. Chu, K. Debnath, L. Goel, E. Khan, P. Kos, G. Nourbakhsh, and J. Oteng-Adjei, "A Reliability Test System for Educational Purposes-Basic Data," *IEEE Trans. Power Syst.*, vol. 4, no. 3, pp. 1238–1244, 1989.
- [19] T. K. Vrana, Y. Yang, D. Jovcic, S. Denetière, J. Jardini, and H. Saad, "The CIGRE B4 DC Grid Test System," *Cigre Electra*, vol. 270, no. 9, pp. 10–19, 2013.
- [20] CIGRE Task Force TF-C6.04, "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources," *CIGRE Tech. BROCHURES*, vol. 575, pp. 1–119, 2014.
- [21] K. Strunz, N. Hatziaargyriou, and C. Andrieu, "Benchmark Systems for Network Integration of Renewable Energy Resources," *Cigre Task Force C 6.04-02*, vol. 78, pp. 1–6, 2009.
- [22] L.T.G. Lima, Thierry Van Cutsem, Mevludin Glavic, William Rosehart, Jhonatan Santos, Claudio Cañizares, Marios Kanas, Federico Milano, Lampros Papanagelis, Rodrigo Andrade Ramos, Behnam Tamimi, G.N. Taranto, and Costas Vournas, "IEEE PES Task Force on Test Systems for Voltage Stability Analysis and Security Assessment, TR-19," 2015.
- [23] CGRE WG 14.02, "The CIGRE HVDC Benchmark Model: A New Proposal with Revised Parameters," *CIGRE ELECTRA*, vol. WG (TF), no. 14.02, pp. 1–6, 1994.
- [24] J. Cao, W. Du, H. F. Wang, and S. Q. Bu, "Minimization of Transmission Loss in Meshed AC/DC Grids With VSC-MTDC Networks," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3047–3055, Aug. 2013.
- [25] K. Fischer, K. Pelka, A. Bartschat, B. Tegtmeier, D. Coronado, C. Broer, and J. Wenske, "Reliability of Power Converters in Wind Turbines: Exploratory Analysis of Failure and Operating Data from a Worldwide Turbine Fleet," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6332–6344, 2018.
- [26] M. Farrokhbadi, C. A. Canizares, J. W. Simpson-Porco, E. Nasr, L. Fan, P. Mendoza-Araya, R. Tonkoski, U. Tamrakar, N. D. Hatziaargyriou, D. Lagos, R. W. Wies, M. Paolone, M. Liserre, L. Meegahapola, M. Kabalan, A. H. Hajimiragha, D. Peralta, M. Elizondo, K. P. Schneider, F. Tuffner, and J. T. Reilly, "Microgrid Stability Definitions, Analysis, and Examples," *IEEE Trans. Power Syst.*, no. DOI: 10.1109/TPWRS.2019.2925703, pp. 1–1, 2019.
- [27] L. M. Moore and H. N. Post, "Five Years of Operating Experience at a Large, Utility-Scale Photovoltaic Generating Plant," *Prog. Photovoltaics Res. Appl.*, vol. 16, no. 3, pp. 249–259, 2008.
- [28] B. Hahn, M. Durstewitz, and K. Rohrig, "Reliability of Wind Turbines - Experience of 15 Years with 1500WTs," *Wind Energy*, no. January, pp. 329–332, 2005.
- [29] A. Golnas, "PV System Reliability: An Operator's Perspective," *IEEE J. Photovoltaics*, vol. 3, no. 1, pp. 416–421, 2013.

- [30] S. Peyghami, H. Wang, P. Davari, and F. Blaabjerg, "Mission Profile Based System-Level Reliability Analysis in DC Microgrids," *IEEE Trans. Ind. Appl.*, no. DOI:10.1109/TIA.2019.2920470, pp. 1–13, 2019.
- [31] S. Peyghami, P. Davari, and F. Blaabjerg, "System-Level Reliability-Oriented Power Sharing Strategy for DC Power Systems," *IEEE Trans. Ind. Appl.*, no. DOI:10.1109/TIA.2019.2918049, pp. 1–11, 2019.
- [32] X. Wang and F. Blaabjerg, "Harmonic Stability in Power Electronic Based Power Systems: Concept, Modeling, and Analysis," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2858–2870, 2019.
- [33] "Power Systems Test Case Archive." [Online]. Available: <http://labs.ece.uw.edu/pstca/>. [Accessed: 25-Feb-2019].
- [34] "IEEE Benchmarks." [Online]. Available: <https://hvdc.ca/knowledge-base/topic:51/v/>. [Accessed: 25-Feb-2019].
- [35] "Electric Grid Test Cases." [Online]. Available: <https://electricgrids.engr.tamu.edu/electric-grid-test-cases/>. [Accessed: 25-Feb-2019].
- [36] "Free, Open-Source Electric Power System Simulation and Optimization Tools for MATLAB and Octave." [Online]. Available: <http://ieeexplore.ieee.org/document/5491276/>. [Accessed: 25-Feb-2019].