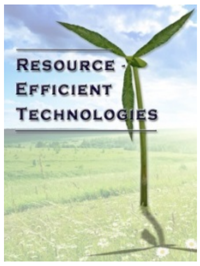
TOMSK POLYTECHNIC UNIVERSITY

Resource-Efficient Technologies 3 (2019) 1–12

Resource-Efficient Technologies

journal homepage: http://ojs.tpu.ru/index.php/res-eff



Review Paper

COMPREHENSIVE REVIEW OF RADIAL DISTRIBUTION TEST SYSTEMS FOR POWER SYSTEM DISTRIBUTION EDUCATION AND RESEARCH

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Abstract

A comprehensive review of existing radial distribution test systems available for power system distribution research is presented. The review can be used to establish a record of cases suitable for distribution operation and planning studies. The importance of the distribution system, the structure of the system in the grid, and various configurations of the distribution network are discussed. The primary requirement of a distribution network is highlighted to underline the important system parameters that should be considered in the design and planning stages. Various research related to the distribution network can be conducted, such as load flow algorithms, optimal incorporation of distributed generation, network reconfiguration, and optimal capacitor allocation, such as important details pertaining to each test system are given. Additional information, such as active and reactive loads and losses, minimum voltage values, and bus location with the weakest voltage values, is provided. Application of the reviewed works based on the test system is tabulated and presented. The information presented in this paper will be beneficial for future research in distribution system design and planning.

Keywords: Radial systems, distribution, power systems, test systems.

1. Introduction

Test systems are widely used in power system studies. Researchers often use these systems as benchmarks to implement their proposed algorithm to evaluate its effectiveness and robustness. However, despite similar configurations, test systems vary. Some test systems are modified to suit particular applications. Changes in the line or bus data will significantly impact the behavior and characteristics of the power system. Therefore, to streamline research efforts, a comprehensive record of various distribution test systems with pertinent network information is required.

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☆ Peer review under responsibility of Tomsk Polytechnic University.
https://doi.org/10.18799/24056537/2019/2/196

Distribution networks often employ simple and cost-effective radial connections [1]. System laterals are connected to a main power source. A time grading-based protection system can be implemented to ensure that tripping occurs in a stage by stage manner for downstream nodes. Various distribution system investigations based on planning and operation have been carried out. Thus, a comprehensive summary comprising all distribution networks is required to ensure that researchers can easily benchmark the solution and verify their algorithm's effectiveness. To address this, this paper presents a comprehensive review of the most commonly used radial distribution test systems that includes network diagrams, respective network data, and power flow results. The main goal of this paper is to offer the research community the ability to investigate various test systems for operation and planning studies on radial distribution systems.

The following information is provided.

- Network diagram: a distribution system connection diagram indicating the bus number and the loads connected in each bus
- Network data: line and bus data information (R and X in p.u.), active and reactive power load, and the S_{base} and V_{base}
- Load flow study: total active and reactive power losses, and the bus where the minimum voltage is obtained
- The original reference for further information.

In this paper, MATPOWER [2] has been used to simulate power flow studies using the Newton-Raphson (NR) and power summation algorithms. In addition, a function that converts MATPOWER cases to VSOP [3] cases is developed. All code, extended data, and the editable diagrams for the various test systems can be obtained by contacting the corresponding author via email.

The remainder of this paper is organized as follows. Section 2 provides an overview of distribution systems and the associated network configurations. Distribution studies are reviewed in Section 3, and a comprehensive test system summaryis given in Section 4. Applications of the reviewed studies based on the test systems are listed in Section 5, and conclusions are presented in Section 6.

2. Overview of distribution systems

Depending on the task, there are many different voltage levels for each stage in the power system network. The ultra-high voltage grid is used to transmit power from large power plants over long distances. The high voltage grid is either connected to large industries or stepped down through distribution substations to low voltage grids. To serve customers and end users of the low voltage grid, the voltage is further stepped down to 230/400 V. If power requirements are high, large industries can be connected to the medium voltage grid. A general overview of connections and voltage levels is shown Figure 1 [4].

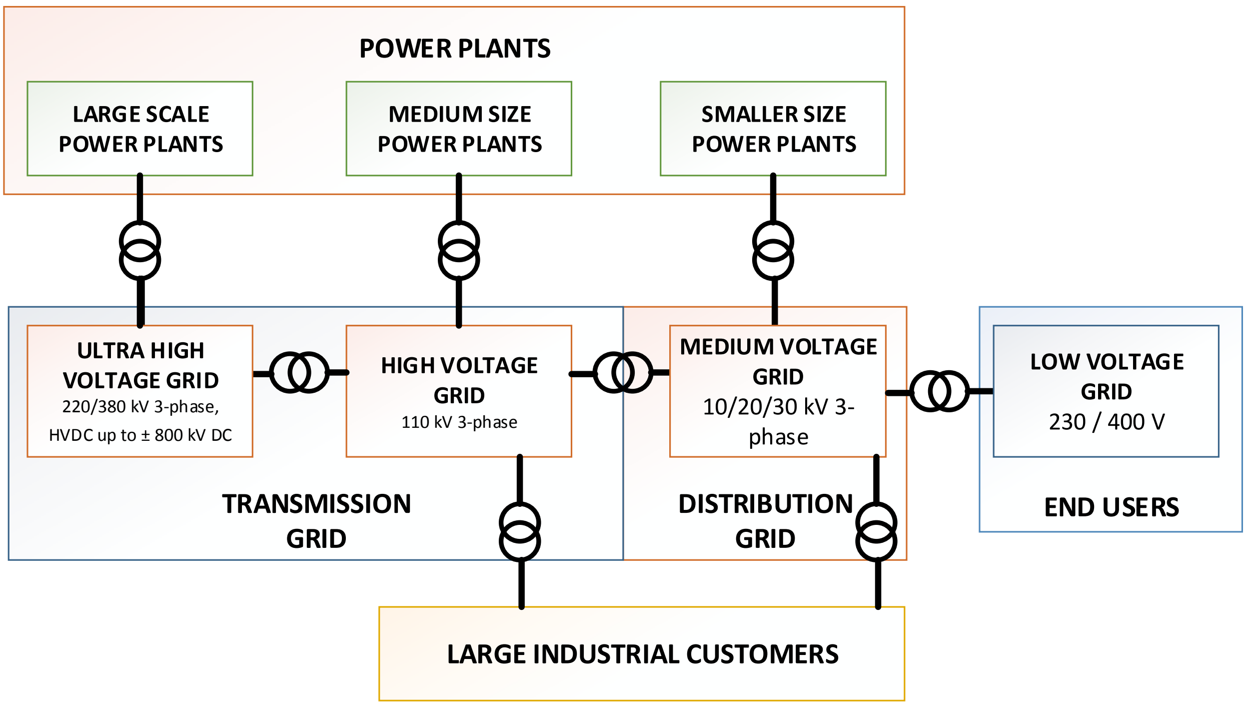


Fig. 1 . General grid structure (Union for the Coordination of Transmission of Electricity) [4]

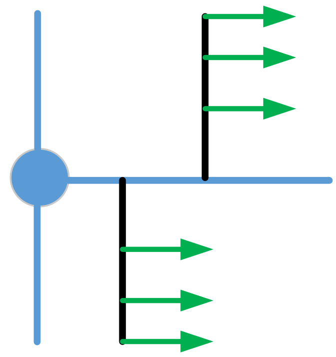
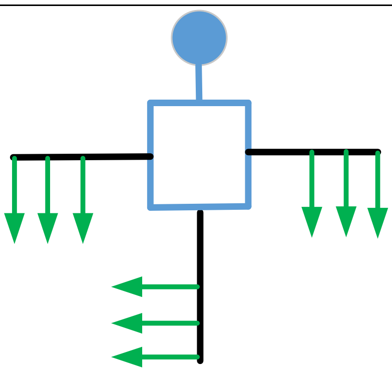
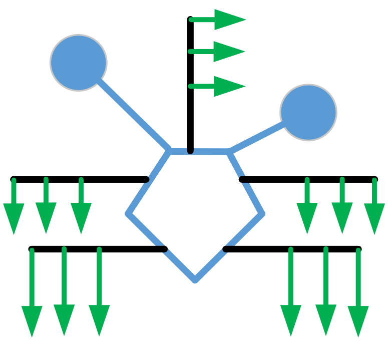
The distribution system is the section of an electric power system that provides electric power to the customer from transformation points located on the transmission system [5]. The distribution system or network comprises feeders, distributors, and service mains [6]. These three primary components are responsible for delivering and distributing power to end users.

- Feeders: The feeders are the main conduits in a substation that connect the substation (power source) to the area where the power is required. Typically, no tappings are taken from the feeders. The feeder endpoints are connected to the distributors.
- Distributors: The tappings for the end users are taken from this point. The main consideration here is the voltage drop since various tapping will introduce a voltage drop on the distributor.
- Service mains: Service mains are the cables that connect distributors to end users.

Figure 2 shows a general connection diagram of a typical low voltage distribution system. The figure illustrates how power is delivered from a distribution substation to the end users through the feeders, distributors, and service means.

The distribution systems, which are connected using overhead or underground cables, have different network configurations. The network configurations describe the connection between the loads and the power source. The three general configurations used in a distribution network and their advantages and disadvantages listed in Table 1 [6].

Table 1 . Common distribution system network configurations

Network configuration	Network connection	Description
Radial network		Radial networks are also known as spur networks. **Advantages** Radial networks are simple to configure because the source is fed at one end. Protection coordination and network monitoring are easy. Depending on network size, capital requirements are relatively low. **Disadvantages** Voltage fluctuation occurs for consumers at the end of the distribution network if the total connected load changes. Spur networks will cause end users to be disconnected (no power supply) if a fault occurs on the feeder or distributor they are connected to.
Ringed network		**Advantages** Power is supplied from both ends. In case of fault in the feeder, power can be supplied from the other end, fewer voltage drops along the line, and less voltage fluctuation. More end users can be connected to the system compared to a radial network. **Disadvantages** Investment costs are higher due to complex protection coordination (line differential protection). Switching operation for fault localization is more complex
Meshed network		**Advantages** Connecting more than a single power source / substation increases reliability. Power can be supplied from different generating stations during peak load hours, which increases efficiency. **Disadvantages** Complex protection coordination due to power flows from different sources is required.

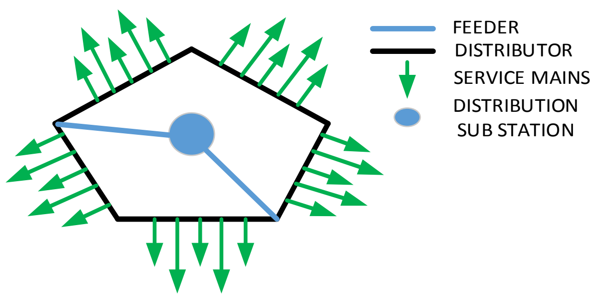


Fig. 2. General overview of low voltage distribution system

In this paper we are interested in radial distribution systems.

3. Distribution studies

RDS test systems can be used in distribution systems for various purposes and studies, some of which are described in the following subsections.

3.1. Load flow analysis

Load flow analysis, which is considered basic analysis for both transmission and distribution systems, provides the voltage and phase angle of the bus in the network at the transmission or distribution level. From these parameters, other parameters, such as power flow and power loss, can be determined. Low flow analysis is applied in the planning and design stages of distribution systems as well as during the operational stage. Transmission and distribution systems have different characteristic; thus, load flow analysis methods are formulated differently. For transmission systems, the NR and fast decoupled methods are well known. The backward–forward method is commonly employed in distribution systems. In such systems, researchers use test systems to validate new load flow algorithms.

3.2. Radial distribution system planning

Generally, distribution system planning involves development and enhancement of an existing system. In the development stage, the primary consideration is minimizing the design cost. In this stage, the overall system design, such as location of substations (HV and MV), medium voltage (MV) feeder routing, load points, and transformer capacity, need to be determined to minimize cost. At the same time, the development must also consider technical constrains, such as maximum allowable voltage drops at load nodes and the maximum load carrying capacity of lines at peak load. For existing systems, the primary consideration is to minimize operation costs and maximize system reliability.

3.3. Optimal conductor size selection

One of the important aspects of designing cost-effective and reliable distribution systems is to determine the optimal size of conductors for the network. Withoud optimization,the selection of conductors will yield high power losses, which translate into high operating costs. Therefore, the primary objective of this study is to minimize energy losses and investment costs subject to feasible operation constraints. Various parameters need to be considered in the formulation of optimal conductor sizing, such as discount rate, economic lifetime of the conductor, cable and installation costs, and circuit type (underground or overhead). This study is also required for a reconductoring process when (1) enormous power losses are encountered in the existing scenario, (2) violation of maximum current capacity is observed, or (3) voltage amplitude in the EDS is less than its lowest threshold.

3.4. Optimal siting and sizing of distribution generation

Maximizing the potential benefit of distribution generation (DG) systems is challenging. DG behavior is influenced by site (location) and size. A major challenge in determining the location is the type of DG. The main types are variable power systems(intermittent sources) and systems with predictable power output [7]. Variable power DGs, such as wind and photovoltaic, are limited by meteorological and geographic factors. DGs with predictable power output, such as fuel cells and microturbines, are mobile and can be placed anywhere. Optimal DG placement (ODGP) is also a challenging problem with critical importance because nonoptimal placement might increase power losses and operating costs [8]. Optimal placement will guarantee improved network performance, power quality, and reliability of supply. Researchers have used various objective functions for the ODGP problem, such as minimization of power loss, cost, voltage deviations, and the system average interruption duration index and maximization of profit and voltage limit loadability. The size of the DG is not based on power consumption in the area alone; careful consideration has to be taken to ensure that total power loss of system remain below the predefined threshold [9]. Load flow analysis, such as optimal power flow, is used to find the optimal DG size that can satisfy the pre-defined criteria. Reliability analysis, which comprises reliability index calculation, restoration analysis, protection / coordination analysis, fault analysis, load flow analysis, and load estimation, also must be performed to determine the optimal DG location and size [10].

3.5. Optimal location and size of capacitors

Capacitors are energy storage devices that are used for a variety of purposes in a power system. In a distribution system, capacitors are primarily used to compensate reactive power loss. High reactive power losses lead to many issues in the distribution network, such as high system loss, high voltage drops, and low power factors [11]. Among the challenges faced in integrating the capacitor into a distribution system is determining the location, size, type, and controls scheme of the capacitor. Incorrect sizing and location reduces system benefits and can result in disturbances in the voltage profile, increased power loss, and an unfavorable power factor [12]. Objective functions, such as minimization of total system losses, minimization of bus voltage violations, and load balancing in feeders are considered in the capacitor sizing and location problem. Capacitor placement and sizing in the distribution network must be carefully considered since the network comprises linear and nonlinear loads. Therefore, power quality constraints are included to ensure that issues such as harmonics occurrence are prevented. Current research has highlighted the importance of switching transient overvoltage of capacitor banks, which is a critical power quality issue that would negatively impact the reliability of a distribution network [13]. Thus, optimal sizing and location of the capacitor will guarantee lower system loss, greater system benefits, an improved voltage profile, and enhanced power quality [14].

3.6. Network reconfiguration

Reconfiguring a distribution system's network requires optimization techniques. Typically, networks are reconfigured to reduce the real power loss. Reconfiguration can also enhance the quality of the electrical power and improve system reliability and security. Network reconfiguration involves the selection of switches. Determining the best set of switches, which must be open to optimize the network, is achieved via optimization. It The operation of switches should fulfill optimization requirements and satisfy all operating constraints. It is important to note that reconfiguring the network is cost effective and much simpler than other techniques.

4. Summary of test systems

A summary of radial distribution test systems is given in Table 2. Note that the numbers in column two in both Table 2 and Table 3 refer to the references listed at the end of this paper.

5. Applications of systems in the

In Table 3, some examples of applications of the RDS presented in this paper are given. The name of the RDS is listed in the first column. The second and third columns list the references and the year of use, respectively, and the fourth column describes the type of study. It is worth mentioning that, even though a long list of references is given in Table 3, the list is not exhaustive and other studies can be found in the literature.

6. Conclusion

This paper has presented a comprehensive review of common radial distribution test systems used in the majority of power system literature. This information presents comprehensive and organized information to facilitate further research and education in distribution system operation and planning. The important properties of the distribution system and the applications referenced in various distribution studies are provided to highlight the importance of distribution system research. The structured table and the contributions of the reviewed works are provided. We hope that this paper will help researchers, academics, and students in distribution system related research work.

Table 2. Summary of radial test systems

Name	Reference	V_{base} kV	Total active power load kW	Total reactive power load kVAr	Total active power losses kW	Total reactive power losses kVAr	Minimum voltage value in p.u	Minimum voltage is at bus
10-bus RDS	[15]	23	12368.0000	4186.0000	783.7754	1036.4710	0.838	10
12-bus RDS	[16]	11	435.0000	405.0000	20.7135	8.0410	0.943	12
15-bus RDS (1)	[17]	11	1226.4000	1251.1785	61.4960	57.0393	0.945	13
15-bus RDS (2)	[18]	11	1226.4000	1251.1785	41.4752	38.4636	0.962	13
16-bus RDS (1)	[19] & [20]	12.66	28700.0000	5900.0000	312.7765	361.1848	0.981	12
16-bus RDS (2)	[21]	12.66	28700.000	5900.0000	511.4004	590.3684	0.969	11
17-bus RDS	[22]	23	13880.0000	5640.0000	950.6711	675.1011	0.885	11
18-bus RDS	[18]	11	1410.5000	1438.8000	58.6080	54.6710	0.951	18
22-bus RDS	[23]	11	662.4600	657.4500	17.6732	9.0439	0.973	22
28-bus RDS	[16]	11	761.0400	776.4190	68.8195	46.0420	0.912	26
33-bus RDS	[24]	12.66	3715.0000	2300.0000	202.6771	135.1410	0.913	18
34-bus RDS	[25]	11	2873.5000	4636.5000	217.0102	63.7539	0.956	27
38-bus RDS	[26]	12.66	3715.0000	2300.0000	202.6771	135.1410	0.913	18
51-bus RDS	[27]	11	2463.0000	1569.0000	129.5559	111.6835	0.908	16
51-bus RDS	[28]	22	1924.0500	1060.3600	24.2918	47.5025	0.969	19
69-bus RDS	[29]	12.66	3802.1000	2694.7000	225.0007	102.1648	0.909	65
70-bus RDS	[30]	11	5385.4000	3687.6000	341.4270	307.5841	0.884	67
74-bus RDS	[31]	11	6617.0000	4447.0000	145.1363	109.9673	0.954	57
85-bus RDS	[17]	11	2514.2800	2565.0783	299.3075	187.8123	0.874	54
94-bus RDS	[32]	15	4797.0000	2323.9000	362.8578	504.0420	0.848	92
118-bus RDS	[33]	11	22709.7200	17041.0680	1298.0916	978.7361	0.869	77
136-bus RDS	[34]	13.8	18313.8070	7932.5680	320.3639	702.9474	0.931	117

Table 3. Examples of radial test system applications

Test system	References	Year	Application
10-bus RDS	[35]	2008	Optimal capacitor placement
	[36]	2011	Optimal Var planning
	[37]	2013	Optimal siting and sizing (OSS) of shunt capacitors
	[38]	2013	OSS of DG and capacitor
	[39]	2013	Analysis of RDS optimization with FACTS devices
	[40]	2013	Capacitor placement
	[41]	2013	Optimal capacitors sizing
	[42]	2014	OSS of capacitors
	[43]	2014	Optimal allocation of capacitors
	[44]	2015	Power factor and energy loss cost evaluation
	[45]	2016	Optimal capacitor placement and sizing
	[46]	2016	Optimal sizing of capacitors
	[47]	2016	OSS of shunt capacitors
12-bus RDS	[48]	2006	Load flow
	[49]	2009	OSS of DG
	[50]	2012	OSS of DG
	[51]	2013	Placement of wind and solar based DGs
	[52]	2013	Optimal allocation of combined DG and capacitor

	[53]	2014	OSS of DG and DSTATCOM
	[44]	2015	Power factor and energy loss cost evaluation
	[54]	2017	Optimal allocation of DG and DSTATCOM
15-bus RDS	[51]	2013	Placement of wind and solar based DGs
	[42]	2014	OSS of capacitors
	[55]	2015	OSS of capacitors
16-bus RDS	[56]	2010	Optimal DG allocation
	[57]	2013	Optimal DG allocation
	[58]	2013	Optimal DG allocation and network reconfiguration
	[59]	2014	Network reconfiguration
17-bus RDS	[60]	2013	OSS of DG
	[61]	2014	OSS of DG
28-bus RDS	[62]	2013	Power Loss Allocation
33-bus RDS	[63]	2011	Simultaneous allocation of DG and remote controllable switches
	[64]	2011	Dynamic network reconfiguration
	[65]	2012	OSS of DG
	[60]	2013	OSS of DG
	[66]	2013	Network reconfiguration
	[38]	2013	OSS of DG and capacitors
	[52]	2013	OSS of DG and capacitors
	[67]	2013	Optimal DG allocation
	[51]	2013	Placement of wind and solar based DGs
	[58]	2013	Optimal DG allocation and network reconfiguration
	[40]	2013	Capacitor placement
	[59]	2014	Network reconfiguration
	[68]	2014	Optimal DG allocation and network reconfiguration
	[69]	2014	Optimal DG allocation and network reconfiguration
	[70]	2014	OSS of DG and shunt capacitors
	[71]	2015	Network reconfiguration and optimal allocation of Photovoltaic and DSTATCOM
	[72]	2015	Simultaneous Planning of PEV Charging Stations and DGs
	[73]	2015	Optimal reactive power control of DGs for
	[74]	2015	Optimal allocation of DG and capacitors
	[75]	2015	Dynamic planning of DG
	[76]	2015	Network reconfiguration
	[77]	2015	Optimal siting of DG
	[78]	2016	OSS of DG
	[79]	2016	Optimal Location of DG
	[80]	2017	Incorporation of DG and shunt capacitor
34-bus RDS	[35]	2008	Optimal capacitor placement
	[40]	2013	Capacitor placement
	[39]	2013	Analysis of RDS optimization with FACTS devices
	[42]	2014	OSS of capacitors
	[43]	2014	Optimal allocation of capacitors
	[81]	2015	OSS of capacitors
	[82]	2015	Network reconfiguration
	[46]	2016	Optimal sizing of capacitors
	[47]	2016	OSS of shunt capacitors
	[54]	2017	Optimal Allocation of DG and DSTATCOM
38-bus RDS	[83]	2013	OSS of DG
	[84]	2013	Optimal allocation of DG
	[85]	2015	OSS of DG
	[86]	2015	DG planning
51-bus RDS	[27]	2015	OSS of DG
	[87]	2016	Optimum placement of shunt capacitors
69-bus RDS	[88]	2001	Network reconfiguration
	[89]	2006	OSS of DG
	[49]	2009	OSS of DG
	[56]	2010	Optimal DG allocation

	[90]	2010	Determination of the maximum allowable penetration level of DG
	[91]	2010	Optimal Sizing of DG
	[92]	2011	Optimal planning of multiple DG
	[50]	2012	OSS of DG
	[65]	2012	OSS of DG
	[37]	2013	OSS of shunt capacitors
	[66]	2013	Network reconfiguration
	[93]	2013	OSS of DG
	[94]	2013	Optimal siting of DG
	[57]	2013	Optimal DG allocation
	[95]	2013	OSS of DG
	[51]	2013	Placement of wind and solar based DGs
	[96]	2013	Optimal siting of DG
	[53]	2014	OSS of DG and DSTATCOM
	[70]	2014	OSS of DG and shunt capacitors
	[97]	2014	OSS of DG
	[98]	2014	Optimal siting of shunt capacitor
	[99]	2015	OSS of DG
	[55]	2015	OSS of capacitors
	[100]	2015	Impact of load models on DG siting and sizing
	[77]	2015	Optimal siting of DG
	[78]	2016	OSS of DG
	[101]	2016	Multi-conductor feeder design
	[79]	2016	Optimal siting of DG
	[87]	2016	Optimum placement of shunt capacitors
	[45]	2016	Optimal capacitor placement and sizing
	[102]	2016	Optimal siting of DG
	[54]	2017	Optimal Allocation of DG and DSTATCOM
70-bus RDS	[103]	2010	Network reconfiguration
	[104]	2012	Location of Automatic Voltage Regulators
	[105]	2014	Network reconfiguration
	[106]	2015	Network planning
74-bus RDS	[107]	2015	Network reconfiguration
85-bus RDS	[35]	2008	Optimal Capacitor Placement
	[108]	2012	Optimal conductor size selection
	[40]	2013	Capacitor placement
	[39]	2013	Analysis of RDS optimization with FACTS devices
	[43]	2014	Optimal allocation of capacitors
	[98]	2014	Optimal siting of shunt capacitor
	[81]	2015	OSS of capacitors
	[47]	2016	OSS of shunt capacitors
	[101]	2016	Multi-conductor feeder design
	[80]	2017	Incorporation of DG and shunt capacitor
	[109]	2017	Sizing of renewable resources
94-bus RDS	[59]	2014	Network reconfiguration
	[78]	2016	OSS of DG
118-bus RDS	[93]	2013	OSS of DG
	[110]	2013	Network reconfiguration and DG planning
	[95]	2013	OSS of DG
	[97]	2014	OSS of DG
	[99]	2015	OSS of DG
	[55]	2015	OSS of capacitors
	[77]	2015	Optimal siting of DG
	[79]	2016	Optimal siting of DG
	[45]	2016	Optimal capacitor placement and sizing
136-bus RDS	[103]	2010	Network reconfiguration
	[64]	2011	Dynamic network reconfiguration
	[100]	2015	Impact of load models on DG siting and sizing

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Received: 12.07.2019