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Review

Optimal operation of smart distribution networks: A review of models, methods and future research

Vasileios A. Evangelopoulos, Pavlos S. Georgilakis*, Nikos D. Hatziargyriou

School of Electrical and Computer Engineering, National Technical University of Athens (NTUA), GR 15780 Athens, Greece

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ABSTRACT

The management of distributed energy resources (DER) in power distribution systems and the concept of demand side management (DSM) are becoming increasingly important in recent years, provided that emerging communication technologies contribute to the formation of smart distribution networks of the future. Several methods have been proposed in the literature for the optimal operation of smart distribution networks (OOSDN) with renewables and/or non-renewable DER, DSM and energy storage systems. The main scope of this paper is to review the most significant papers in the area of OOSDN and to introduce a taxonomy of models and optimization methods that are applied to the OOSDN problem. Moreover, the basic schemes for active network management are briefly presented. The article also discusses challenges and areas for future research in the field of OOSDN.

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* Corresponding author. Tel.: +30 210 772 4378; fax: +30 210 772 3659.
E-mail addresses: vevangel@power.ece.ntua.gr (V.A. Evangelopoulos), pgeorg@power.ece.ntua.gr (P.S. Georgilakis), nh@power.ece.ntua.gr (N.D. Hatziargyriou).

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Nomenclature

Acronyms

AMI	advanced metering infrastructure
ANM	active network management
APFC	adaptive power factor control
AROPF	active-reactive optimal power flow
BB	branch and bound
BSS	battery storage system
CHP	combined heat and power
CSP	constrained satisfaction problem
CVC	coordinated voltage control
DER	distributed energy resource
DERC	distributed energy resource control
DG	distributed generation
DMS	distribution management system
DP	dynamic programming
DR	demand response
DSM	demand side management
DSO	distribution system operator
EA	evolutionary algorithm
EENS	expected energy not supplied
EMS	energy management system
ESAIFI	expected system average interruption frequency index
ESM	energy storage management
ESS	energy storage system
FD	flexible demand
FDG	fuelled distributed generation
GA	genetic algorithm
GC	generation curtailment
GT	gas turbine
ICE	internal combustion engine
ICT	Information and Communication Technologies
IED	intelligent electronic device
IP	interior point
LP	linear programming
MAS	Multi-Agent System
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
MIQC	mixed integer quadratic constrained
MPC	model predictive control
MRCGA	matrix real coded genetic algorithm
NLP	non-linear programming
NRM	network reconfiguration management
OLTC	on-load tap changer
OOSDN	optimal operation of smart distribution network
OPF	optimal power flow
PCC	point of common coupling
PEM	point estimate method
PPF	probabilistic power flow
PV	photovoltaics
QP	quadratic programming
RCS	remote control of tie switches
RES	renewable energy source
RL	responsive load
RM	reserve management
RPC	reactive power compensation
RTU	remote terminal unit
SA	simulated annealing
SCADA	supervisory control and data acquisition
SDN	smart distribution network
ShC	shunt capacitor
ShR	shunt reactor
SVC	static var compensator
SVR	step voltage regulator
TN	transmission network
VSF	voltage-sensitivity factor
VUF	voltage unbalance factor
VVO	volt/var optimization
WT	wind turbine

1. Introduction

Power distribution networks are in a transformation from passive to active distribution networks, also called smart distribution networks (SDNs), owing to the fast development of emerging Information and Communication Technologies (ICT), and the integration of advanced metering infrastructure (AMI). Supervisory control and data acquisition (SCADA) systems are used for monitoring the power distribution system, while distribution management systems (DMS) and energy management systems (EMS) act as decision support information systems for the coordination of network remote devices. The main reason for this transformation is the need to accommodate the high penetration of distributed generation (DG), especially renewable energy sources (RES), in order to meet the environmental targets for gas emission reduction and sustainability. However, conventional power distribution systems have been designed assuming that the HV/MV substation is the sole power source; therefore, the growth of DG incorporation implies technical issues that should be taken into consideration for the efficient and reliable operation of power distribution systems.

Optimal operation of smart distribution networks (OOSDN) plays an important role for the sufficient power delivery to consumers, the integration of RES and the economic energy management. The operation of power distribution systems can be divided into: (1) *real-time operation*, when actions and commands occur in short time periods and are based on communication signals and state-estimation algorithms, and (2) *scheduled operation*, in which an one day (or more days) ahead schedule is planned based on demand and renewable power generation forecasting.

SDNs can be optimally operated by exploiting the sophisticated control capabilities of distributed energy resources (DER) and taking advantage of SDN components and intelligent electronic devices (IEDs). The OOSDN aims at the accommodation of high penetrations of renewable and non-renewable DER and the coordination of them with voltage regulation devices and energy storage systems (ESS). Therefore, the OOSDN can induce efficient power distribution systems, reduction of power losses, improvement of power quality, reliability, capability for higher DG penetration and satisfaction of energy consumers.

Distribution system operator (DSO) is responsible for the OOSDN by applying the suitable Active Network Management (ANM) schemes in order to satisfy network constraints with the most efficient way in compliance with the regulatory framework and the energy policies of each territory. In recent years, the problem of OOSDN has attracted the interest of many research articles. We collected a big number of such articles to be reviewed. Next, we studied all these articles and we finally selected the subset of high quality articles [1–57], which we review in our paper, taking also into account the page limitations. With this approach, our review paper is aiming to outline all the requisite and useful information for academia and industry.

The works [58–65] have discussed the challenges and the technologies of SDNs. However, they do not classify models and methods for optimal operation schedule or efficient real-time operation, as this paper does. More specifically, in [58], emerging communication technologies and management techniques for active distribution networks are outlined. In [59], the main reasons for passing to the smart grid era are discussed, the basic attributes of smart grid concept and the requirements needed for DER incorporation are described by reviewing recent works. In [60,61], the impacts of high DG penetration are addressed. The authors of paper [60] also describe and highlight the need for employing ANM technologies. The benefits and the impact of voltage and reactive control of smart grids are outlined in [62]. A comprehensive review of techniques and algorithms for optimal DG planning is outlined in [63,64]. The authors of [64] also discuss the issue of the efficient DG control and the employment of different ANM schemes as a future challenge. A review of the multi-year planning of smart distribution networks can be found in [65].

The main contributions of this paper are: (1) the taxonomy of ANM schemes and models that are applied to the OOSDN, (2) the classification of algorithms and methods for the OOSDN, and (3) recommendations and trends for future research in the field of OOSDN. The taxonomy table, i.e., Table 1, provides all the information needed for the OOSDN problem, i.e., SDN components, the type of DER, load model, ANM schemes, control variables and objective functions. Therefore, this review can be used as a guide by researchers and power system engineers working in the area of OOSDN.

The paper is organized as follows. Sections 2 and 3 classify and describe the ANM schemes and the models of OOSDN, respectively. Section 4 classifies the methods used for solving the problem of OOSDN and it also identifies the main contributions of the reviewed works. Section 5 recommends future work and Section 6 concludes.

2. ANM Schemes for OOSDN

The main purpose of ANM is the optimal utilization of high penetrations of renewable and non-renewable DER, in order to ensure higher power quality performance as it is determined by international standards and regulatory norms. The ANM schemes offer to DSOs the capability to efficiently operate the SDNs and to achieve the objectives, described in Section 3.2, by employing advanced optimal power flow (OPF) techniques that are solved by heuristic, numerical or stochastic methods [66]. Several methods have been deployed to solve the OPF problem and they are analyzed in Section 4.

The ANM schemes, which mostly involve active voltage control and active power flow management, can be classified as follows:

- *Coordinated Voltage Control (CVC):* Voltage regulation devices, equipped with controllers, operate in a coordinative way with all the available types of DER to improve the voltage profile of distribution network. CVC, in combination with var regulation (described below) and DER reactive support is mentioned as Volt/Var Optimization (VVO) [38,62,67].
- *Reactive Power Compensation (RPC):* It refers to the compensation of reactive power by injecting or absorbing reactive power using shunt capacitors or inductors, respectively, or other compensation devices. DERs can also compensate reactive power, as ancillary service, but in this paper distinguish is made between the RPC and the adaptive power factor control (APFC).
- *DER Control (DERC):* It refers to the functionality of controlling the dispatched reactive power of DGs for maintaining the output voltage of DG units at a specified value; this operation mode is also known as P-V mode. The DERC also refers to the ability of adjusting the active power of DERs. DERC, as ancillary service, can actively participate in feeder's voltage regulation and assists in the minimization of network power losses.
- *Adaptive Power Factor Control (APFC):* In this scheme, the DG power factor is optimally adapted depending on the need of DG for either injecting or absorbing reactive power. With the APFC, the DG power factor can be optimally scheduled and dispatched in coordination with other voltage control devices; this operation is also known as P-Q mode.
- *Generation Curtailment (GC):* In the case of RES, power generation may be required to be curtailed due to technical limitations. This scheme is usually implemented when the other means of ANM have been exhausted. The GC is an undesirable means of ANM, because an amount of the available renewable energy is rejected and not supplied. A solution to eliminate GC is to store energy temporarily and dispatch it during the peak load period.
- *Network Reconfiguration Management (NRM):* It refers to the remotely handling of tie switches in order to alleviate line overloads and supply power to consumers through another path. This ANM scheme can enhance the reliability of SDNs.
- *Energy Storage Management (ESM):* Distributed energy storage tends to dynamically participate in the OOSDN from either an economic or a technical point of view. The ESM is applied in order to optimally exploit the energy that is curtailed and not supplied by non-dispatchable DGs. Furthermore, the ESM scheme

Table 1
Taxonomy of the reviewed Active Network Management schemes and models for OOSDN.

Reference	Control variables	DER type	Load profile/ model	ANM schemes	Control	Objective
[1]	1, 2, 5, 12	Dispatch. DG	Multi-level	CVC, RPC, DERC	centralized	min power losses
[2]	1, 5, 6	No DER	24 h-curve	CVC, NRM, RPC	centralized	min {power losses, voltage deviations}
[3]	4	Dispatch. DG	One level	DERC	decentralized	min DG reactive power
[4]	4, 9	Non-dispatch. DG	One level	GC, DERC	centralized	max DG export
[5]	1, 5	WT, hydro	24 h-curve	CVC, RPC	centralized & local	min power losses
[6]	1, 2, 5	PV	Multi-level	CVC, RPC	centralized	min {power losses, voltage deviations}
[7]	1, 8	WT	Real-time	CVC, APFC	centralized	voltage limits satisfaction
[8]	1, 5, 9	WT, PV, GT	Multi-period	CVC, RPC, GC	centralized	min DG curtailment
[9]	11	WT, ESS	24 h-curve	ESM	local	min deviations between wind power and optimal dispatch
[10]	1, 2, 8, 9, 10	WT	Multi-period	CVC, APFC, GC	centralized	max DG capacity
[11]	1, 2, 5	WT	Stochastic	CVC, RPC	centralized	voltage limits satisfaction
[12]	1, 8, 9, 10	WT	multi-period	CVC, GC, APFC	centralized	max wind energy exploitation
[13]	1, 3, 4	{WT, PV} {GT, ICE, CHP biomass}	24 h-curve and real-time	CVC, DERC	centralized	min {voltage deviations, scheduled DG deviations, network losses}
[14]	4	WT	Real-time	CVC, DERC	decentralized	min voltage deviations
[15]	11	BSS, PV, WT	No load	ESM	local	min deviations between output power and forecasted dispatch of RES
[16]	7	DR	24 h-curve	DSM	local	max consumer utility
[17]	1, 4	WT, biomass	Max–min load	CVC, APFC	centralized	max reactive power injections
[18]	1, 2, 8, 10	WT	Multi-period	CVC, APFC	centralized	min energy losses
[19]	3, 11	PV, WT, ESS, dispatch. DG	24 h-curve	DERC, ESM	centralized	min operational costs of microgrid
[20]	2, 4, 5	RES, dispatch. DG	Multi-level and real-time	CVC, RPC, DERC	decentralized	voltage limits satisfaction
[21]	11	PV, BSS	24 h-curve and real-time	ESM	local	min cash flow (min end-user bill)
[22]	1, 3, 4, 7	WT, FDG, DR	Multi-level	CVC, APFC, DSM	centralized	max profit
[23]	1, 5	No DER	24 h-curve	CVC, RPC	centralized	min {energy import, switching operations}
[24]	4, 6, 7, 9	WT, GT, DR	24 h-curve	DERC, GC, DSM	centralized	min operation cost of ANM schemes
[25]	1, 8	WT, biomass	Multi-period	CVC, APFC	centralized	min reactive support from TN
[26]	1, 2	any DG type	Real-time	CVC	decentralized	voltage limits satisfaction
[27]	1, 2, 3, 4, 5	WT, PV, dispatch. DG	One level and real-time	CVC, DERC, RPC	decentralized	min {voltage deviations, switching operations, DG reactive power}
[28]	3, 4	Dispatch. DG	One level	CVC, DERC	decentralized	voltage limits satisfaction
[29]	1, 2, 5, 11	PV, BSS	Real-time	CVC, ESM	centralized	min tap changes & peak load shaving
[30]	6	WT, PV dispatch. DG	One level	NRM	centralized	min power losses
[31]	5	any DG type	One level	RPC	decentralized	min power losses
[32]	1	dispatch. DG	Real-time	CVC	centralized	voltage limits satisfaction
[33]	3, 4, 7, 11	BSS, GT	24 h-curve	ESM, GC, DERC	centralized	min {ANM costs, cost of losses}
[34]	7	DR	24 h-curve	DSM	centralized	min deviations between actual load consumption and objective load curve
[35]	4, 9, 11	WT, BSS	24 h-curve multi-day	DERC, GC, ESM	centralized	max energy exploitation, min energy losses
[36]	3	WT, dispatch. DG	Stochastic	DERC	centralized	min non-RES generation cost
[37]	1, 5, 12	Dispatch. DG, WT	24 h-curve	CVC, RPC, DERC	centralized	min {switching operations, power losses}
[38]	1, 2, 4, 5	Dispatch. DG	Two-level	CVC, APFC, RPC	centralized	min {imported power, voltage deviations}
[39]	11	BSS, PV	24 h-curve	ESM	centralized	min power losses
[40]	1, 4, 5	Dispatch. DG	real-time	CVC, DERC, RPC	decentralized	min {power losses, average voltage deviation, maximum voltage deviation, reactive energy cost}
[41]	1, 5, 12	non-dispatch. DG	24 h-curve	CVC, RPC, DERC	centralized	min {power losses, voltage deviations}
[42]	4, 9, 11	WT, BSS	24 h-curve and multi-day	DERC, GC, ESM	centralized	max energy exploitation & min energy losses
[43]	1, 12	WT, PV	Multi-level and real-time	DERC, CVC	decentralized	min voltage deviations
[44]	1, 3, 4	WT, hydro	Real-time	CVC, DERC	centralized	min changes of control variables
[45]	1, 2, 4	PV	24 h-curve	CVC, APFC	centralized	min tap changes
[46]	3	WT, hydro	Real-time	GC	centralized	min cost of DGs
[47]	6	WT, PV, hydro	Multi-level	NRM	centralized	min {energy losses, ESAIFI and EENS}
[48]	1, 11	BSS, PV, WT	24 h-curve and real-time	CVC, ESM	centralized	min {cost of ESS, cost of OLTC operation)
[49]	1, 5, 6, 8, 9	Non-dispatch. DG	One level	CVC, GC, NRM, RPC, APFC	centralized	min {DG curtailment, switching actions}
[50]	3, 7, 9, 11	WT, ESS, FD	Time-series	GC, ESM, DSM, CVC	centralized	max (energy export, revenue from export}
[51]	6, 9	WT, PV	24 h-curve	NRM, GC	centralized	min {DG curtailment, switching actions}
[52]	3, 5, 13	WT, PV, DR, dispatch. DG	24 h-curve	DSM, RM	centralized	min {total operational costs, emissions}
[53]	1, 3, 4, 5	Dispatch. DG	Multi-level	CVC, DERC	centralized	min {power losses, curtailment cost}
[54]	3, 4, 6, 7	WT, FDG, RL	24 h-curve	DERC, DSM, NRM	centralized	min total operational costs
[55]	11	PV, BSS	24 h-curve and real-time	ESM	centralized & local	min {power losses, voltage deviations, VUF, BSS costs}
[56]	1, 8, 9	WT	Time-series	CVC, APFC, GC	centralized	max wind energy exploitation
[57]	1, 6, 8, 9, 10	WT	Multi-period	CVC, APFC, GC, NRM	centralized	max hosting DG capacity

is employed for avoiding network congestions and serve power during emergency conditions.

- *Demand Side Management (DSM):* This ANM scheme consists of the actions occur for monitoring, supervising and controlling consumers load (residential, commercial or industrial) in order to fulfil the network requirements and the technical specifications by reducing and managing the energy consumption. Not only the utilities, but also consumers use technologies, functionalities and business models for the implementation of DSM projects. The DSM scheme is based on real-time measurements and data acquisition. The fast response of DSM procedures seems to be a challenge for smart distribution grids. The DSM concept is usually based on two pillars: (1) a higher energy price, given as incentive for the abatement of energy consumption and (2) a payoff to consumers, given as compensation for taking their electric load off, when congestions are predicted to occur in the distribution system. The first pillar refers to the variations in the pattern that end-users normally consume energy, in response to the variations of the electricity price, and is known as responsive demand. The second pillar is referred as demand response (DR). DR assists in the reliability of power distribution system and can facilitate the normal system operation. An overview of DSM business models is provided in [68]. Further information about DR and smart grids can be found in [69].
- *Reserve Management (RM):* It refers to the ability of managing the DG reserve and the DR reserve (as load shedding) in order to face unwilling and uncertain scenarios, when the distribution system hosts many non-dispatchable DER.

3. Models for OOSDN

3.1. Problem formulation

The general problem of OOSDN optimizes the operation of SDN by determining the optimum values of control variables subject to technical and operation constraints, the DER specifications and the reliability of power system. The balance between security, economy and quality in SDNs is the overall objective to be met. The OOSDN is mainly a problem based on OPF techniques and, depending on the mathematical model chosen, the constraints, the selected objective functions and the type of control variables (discrete or continuous), the OOSDN can be assumed as a: (1) linear problem, (2) non-linear problem, (3) mixed-integer linear, or (4) mixed-integer nonlinear optimization problem [66].

3.2. Objectives

The main objective functions of OOSDN are: (1) minimization of power losses, (2) minimization of total operational cost, (3) minimization of voltage deviations or voltage unbalance factor (VUF), (4) minimization of DG curtailment, (5) minimization of switching operations of SDN components, (6) minimization of the Expected System Average Interruption Frequency Index (ESAIFI) and the Expected Energy Not Supplied (EENS), (7) minimization of DG reactive power support, (8) minimization of the imported power from Transmission Network (TN), (9) minimization of operational costs of ANM schemes, (10) maximization of DG reactive power injection in order to minimize the imported reactive power from TN, (11) maximization of the exported power to TN, (12) maximization of the total profit of either DSO or consumer, (13) maximization of consumer's benefit, (14) maximization of the installed DG capacity, (15) maximization of RES exploitation and (16) voltage limits satisfaction. The objective functions are directly relevant to the stakeholders who participate in power distribution networks, such as DSOs, energy consumers, DG owners, etc. The objective functions depend on the financial interests of stakeholders and the technical and legal framework.

3.3. Control variables

In the OOSDN bibliography the following twelve control variables are optimized: (1) OLTC (on-load tap changer); (2) SVR (step voltage regulator); (3) DER active power; (4) DER reactive power; (5) reactive compensation with switched shunt capacitors (ShC), shunt reactors (ShR) or Static Var Compensator (SVC); (6) RCS (remote control of tie switches); (7) flexible or responsive load; (8) DG power factor; (9) power curtailed; (10) DG installed capacity; (11) active power charging/discharging; (12) voltage of DG at the point of common coupling (PCC).

3.4. Distributed energy resources (DER) types

The types of DER can be divided as follows:

- Distributed generation (DG) is divided into:
  - Dispatchable DG: This category includes all the types of controllable generation, such as fuelled DGs (FDG), gas turbines (GT), combined heat and power (CHP), hydro, biomass, Internal Combustion Engine (ICE), microturbine, etc. This type of DG can adjust the output on demand and be turned on or off.
  - Non-dispatchable DG: It refers to these DGs that have variable generation, i.e. the DG output cannot be accurately predicted and it cannot be dispatched in predefined time-period by the DSO. It involves the DGs that are characterized by uncertainties like wind turbines (WT) and photovoltaics (PV). Handling the stochastic nature of wind and solar irradiance is the key issue for optimal RES exploitation.
- Energy Storage System (ESS): When charging or discharging, an ESS can be considered as an indirect load or generation, respectively. The most common technology is Battery Storage Systems (BSS). Other ESS technologies include: pumped hydroelectric storage, compressed air energy storage, flywheel energy storage, superconducting magnetic energy storage, etc. The ESS is still considered as an expensive investment. A review of ESS can be found in [70,71].
- Demand response (DR) or responsive load (RL) and flexible demand (FD): The DR is also considered as an energy resource. It refers to the intentional modification of electricity usage by end-use customers during the system imbalances in response to signals predicted by the system. With DR concept, compensation is given to end-users, in contrast with responsive load where the load profile follows the dynamic pricing. According to FD concept, the energy is delivered to consumers by shifting load from the peak load period to the non-peak load period; hence, the total energy consumption can remain the same during the scheduled time-horizon.

3.5. Load model

Different load data models are considered for the OOSDN and are usually related with the operation strategy that is adopted, either the optimal dispatch scheduling or the real-time operation.

In the optimal dispatch scheduling, an OOSDN scheme is determined in advance for one or more days ahead, considering either different load levels (off-peak, on-peak, average or any other desired demand level) or a 24-h load curve. In the case of long term evaluation (i.e., one year), in order to avoid the computational burden, the load and generation data are discretized and aggregated in certain periods (multi-periods). Load data can be either deterministic or stochastic depending on the optimization approach and the assumptions that are made.

On the other hand, in the case of real-time operation, more frequent decisions are made for the OOSDN closer to real-time and they are based on state-estimation algorithms that are catered with either local or remote measurements.

Consequently, the load model can be mainly categorized as follows: (1) daily load profile or time-series, (2) one or multiple load levels, (3) multi-periods (clustering) and (4) real-time.

3.6. Operational requirements and constraints

Towards the smart distribution networks era, consumers are motivated to actively participate in the electricity market via the DR concept, the exploitation of RES tends to be increased, power should be served to consumers with improved reliability and the electricity market is deregulated [66]. These aforementioned characteristics of smart distribution grids have brought new challenges and operational requirements that can be summarized as follows: (a) AMI and ICT integration, (b) low cost sensor infrastructure, (c) consumer-side applications, (d) DER information systems, (e) high performance energy storage, (f) new planning tools for efficient operation of smart distribution grids and (g) training and education on modern topics of 'smart grid' [66,72].

Nevertheless, the distribution networks, the DERs and the SDN components are limited by the following technical constraints: (a) upper and lower limits to the active and reactive power generation, (b) branch thermal limits, (c) network voltage limits, (d) power balance equations and system stability, (e) upper and lower tap changer steps, (f) energy storage charging/discharging capability, (g) substation reverse power flow limitation, etc. There are also constraints related with the regulatory framework, such as: (a) DG curtailment limitation, (b) load shedding constraints, (c) contract terms between DSOs, consumers and DG owners, (d) targets for emission reduction, etc.

3.7. Control architecture

Power distribution systems evolve form passive to smart by taking advantage of the IEDs integration and high-performance ICT. Hence, several control architectures have been investigated and they are divided as follows:

- *Centralized control:* The control decisions are made by a DMS, which is the kernel of the centralized structure. The DMS aggregates measurements and data, executes algorithms for OOSDN based on state estimation and/or forecasting, and broadcasts signals to the controllable SDN components. The centralized approach requires significant investments in the communication infrastructure of utilities.
- *Decentralized control:* In this structure, each SDN component, i.e. OLTC, ShC, or DER, acts as an individual agent. The decisions for OOSDN are determined and act locally, whereas the information is exchanged among the agents. This architecture facilitates and permits the so called 'plug-and-play' concept, is cheaper, simple, and it is based on two-way communications using the control net protocol. This control approach is also known as Multi-Agent System (MAS), distributed control or peer-to-peer control.
- *Local control:* The decisions are made locally and the optimal operation is concentrated on certain SDN components. In contrast with decentralized control, the information is not exchanged among system components, since communication is absent.

3.8. Taxonomy

Table 1 presents a taxonomy of the reviewed ANM schemes and models for OOSDN. In the second column of Table 1, the numbers of control variables are in accordance with the coding of Section 3.3.

4. Methods

Several methods have been recommended in the bibliography to solve the optimization problem of OOSDN. These methods belong to three broad categories: numerical, heuristic and stochastic methods.

Table 2 summarizes the main contributions of the OOSDN works reviewed in this paper in a chronological order. The content of Table 2 can be used in combination with Table 1 that accordingly presents the applied components, models and ANM schemes. Hence, the suitable optimization approach that best fits to each OOSDN problem can be selected by using Tables 1 and 2 as a guide.

4.1. Numerical methods

4.1.1. Exhaustive search

The constrained satisfaction problem (CSP), described in [45], uses discrete percentage levels of DG curtailment to relax network overload; all the possible combinations are calculated as possible solutions and the one with the maximum DG output is selected with respect to a last-in-first-out connection rule.

4.1.2. Linear programming (LP)

In [17] an OOSDN approach is proposed by solving an LP problem to maximize the DG reactive power injection while considering the cooperation with the OLTC system. An LP, considering ESS, is formulated for OPF and is solved to determine the optimal operation schedule taking into account the next time intervals of the time horizon [33]. The optimal active and reactive DG adjustments arise as the solutions of the individual LP problems that the main problem has been divided into; the DG units solely regulate the voltage profile in their neighbour [28]. In [3], the OOSDN is formulated as an LP problem by linearizing the power flow equations in order to minimize the reactive power of DG units that is used as voltage regulation support. An optimal curtailment method is proposed in [4] using the voltage-sensitivity factors (VSFs) in an LP formulation. A well formulated mathematical model for the OOSDN is linearized using the voltage sensitivity coefficients [24]. In [16], a simple LP algorithm maximizes the utility of consumer with a DR model. VVO is modelled in [38,67] as a mixed integer linear programming (MILP) and is solved to optimize the OLTC positions and the switching status of ShC and DG reactive output. In [13], a MILP algorithm optimally updates in real-time the intra-day schedule based on a day-ahead scheduler, using the sensitivity coefficients.

It should be noted that the optimization problems of voltage regulation take advantage of the voltage-sensitivity coefficients to linearize the mathematical model, which significantly reduces the execution time.

4.1.3. Non-linear programming (NLP)

A multi-period AC OPF is formulated as a NLP problem in order to achieve the OOSDN for the maximization of DG capacity in [10]; the minimization of energy losses in [18]; the maximization of DG reactive power support in [25] and the maximization of the energy supplied by DG units in [12]. Considering both the active and reactive dispatch, an active-reactive OPF (AROPF) problem, formulated as NLP, is solved for the OOSDN in [35,42]. An OPF technique is deployed to minimize the costs of DG and maximizes the output power of DG, in [46], whereas it is compared with an analytical approach.

Table 2
Contribution of the reviewed OOSDN works.

Reference	Published	Contribution
[1]	Jun. 2003	A GA is employed for volt/var control for improving the voltage imbalances in a three-phase unbalanced distribution network. The significance of DG installation for voltage regulation, operating with other control devices, is highlighted.
[2]	Aug. 2004	An EA based on fuzzy sets optimizes the operation of a meshed automated distribution system. No DER is present in this work, but switching operations of ShCs, OLTC and RCS are restricted as constraints.
[3]	Feb. 2007	A MAS scheme is introduced for optimal DG reactive power dispatch during emergency conditions. The MAS scheme enhances the plug-and-play integration of DGs.
[4]	May 2007	The optimal GC of RES is examined based on the voltage-sensitivity and loss-sensitivity factors for voltage rise management.
[5]	Nov. 2007	The optimal coordination of OLTC with capacitors is investigated by combining remote and local control. Results are compared with the conventional local control method (i.e., predefined set-points of distribution system equipment).
[6]	Apr. 2008	A central control aims to optimize the cooperation of different types of SDN equipment (e.g., ShC, ShR, SVC, SVR) in the presence of PV generation. A GA-based technique is developed to determine a feasible solution for the large scale problem.
[7]	Apr. 2008	A DMS Coordinated Controller (DMSCC) is deployed for voltage regulation and reactive power management in real time. The DMSCC exploits the integrated state estimator for the effective coordination of OLTC with DG reactive power.
[8]	Oct. 2008	The fuzzy C-means clustering algorithm is used to reduce the input data and solve the optimization problem for different generation and load levels. Several technical-economic indices assess the validity of ANM schemes for OOSDN.
[9]	Jul. 2009	The optimal ESS operation aims at achieving high exploitation of wind power. Results prove the effectiveness of WT-ESS hybrid system whereas the mismatch between wind output and the reference output (OPF result) is decreased.
[10]	Feb. 2010	An AC multi-period OPF approach is recommended to increase the exploitation of DGs by adopting ANM. For this purpose, an innovative method for aggregating the yearly time-series data in periods is introduced.
[11]	May 2010	A PEM-based PPF method is proposed considering load, DG and network topology uncertainties. By taking advantage of a sensitivity matrix for voltage control, that is also proposed, the evaluation of network voltages is being more confident.
[12]	May 2010	A multi-period OPF maximizes the exploitation of wind energy with ANM schemes, similar to [10], but it also considers the short-circuit-level constraint. Results demonstrate that ANM can increase the penetration level of intermittent DG units.
[13]	Sep. 2010	A MINLP is linearized to MILP in a two-stage DMS algorithm. Firstly, an one-day-ahead scheduling is determined and subsequently an intra-day optimization updates the control variables.
[14]	Oct. 2010	A MAS structure improves the voltage profile by coordinating the reactive power output of WTs and considering random connection/disconnection events.
[15]	Oct. 2010	A simple rule-based algorithm optimally dispatches RES by exploiting the available BSS (with high charging/discharging frequency) in the PCC. The proposed model can be easily adapted with other storage technologies.
[16]	Dec. 2010	A robust LP algorithm, which can be installed in a consumer-side EMS, attempts to minimize the electricity bill by exploiting the bidirectional ICT infrastructure of smart grid. Results prove that real-time pricing can reduce the consumer's electricity bill.
[17]	Feb. 2011	The proposed method optimizes the DG power factors and the OLTC settings in order to minimize the reactive power import from the TN. The optimal scheme is identified for the worst scenario and is evaluated by annual time-series.
[18]	Feb. 2011	A multi-period OPF technique minimizes the energy losses with the adoption ANM schemes by taking into consideration the variable nature of demand and uncertain RES output. The way DG capacity affects energy losses is also explored.
[19]	May 2011	A MRCGA optimizes the coordinated operation among BSS, RES and dispatchable DG in a microgrid. This optimization technique takes advantage of a RES power generation forecasting model.
[20]	Jul. 2011	A MAS-based cooperative control structure is described for voltage regulation in unbalanced SDNs. The aim is to mitigate the negative impacts of DGs on voltage profile in real-time.
[21]	Jul. 2011	A DP is used to determine the optimal BSS charging/discharging schedule for peak load shaving, whilst is compared with a rule-based algorithm. Real-time operation simulations demonstrate the effectiveness of the proposed method.
[22]	Oct. 2011	An EMS is recommended for aggregating data acquired by RTUs and it solves a two-stage OPF algorithm. ANM and DSM are integrated in the EMS. Simulations prove that real time implementation of the proposed method is possible.
[23]	Oct. 2011	A novel three-phase distribution OPF model is described for optimal operation of unbalanced distribution systems. The MINLP problem is transformed into NLP for accelerating the computational speed in order to be easily implemented in practice.
[24]	Oct. 2011	A DMS algorithm, which is structured in two stages, aims at reducing the costs of the applied ANM schemes, whereas it searches the optimal network configuration among several potential network topologies.
[25]	Nov. 2011	Two multi-period OPF techniques are proposed by taking advantage of DG reactive power capability and considering N-1 contingencies: 1) control and monitoring with ANM, 2) enhanced passive approach (fixed power factor and OLTC setting).
[26]	Dec. 2011	The proposed technique exploits RTUs, installed on DG buses, to approximately estimate feeder's min and max voltage. Each RTU executes a voltage estimation algorithm and provides data to the upstream RTU for voltage adjustments in real-time.
[27]	Mar. 2012	A MAS structure and a real-time simulation model are proposed in this work. Each SDN component has a controller, which optimizes its own objectives using its own operation mechanism in order to regulate the voltage profile.
[28]	Jun. 2012	With the proposed method, a large secondary distribution network is divided into subnetworks, based on the ε-decomposition of the sensitivity matrix. Voltage regulation is achieved locally by adjusting the active and/or reactive power of DG units. As a result, a better MAS implementation can be achieved, since the communication infrastructure is also divided into subsystems.
[29]	Jun. 2012	A novel coordinated control method is demonstrated on a power hardware in the loop test system. Results prove its effectiveness: voltage profile is improved, tap changes are minimized and peak load is smoothly shaved by BSS discharging.
[30]	Jun. 2012	Three algorithms (optimal NRM, load estimation, unbalanced power flow) are proposed for being employed in a DMS. Simulations demonstrate low computing time, and hence, these algorithms can be applied for the real-time operation of SDN.
[31]	Sep. 2012	An approximate voltage profile estimation is proposed. Based on this, an innovative algorithm is introduced for optimal RPC by utilizing the RTU placement on DGs and/or ShCs, similarly to [26]. Each RTU coordinates with its neighbour RTU.
[32]	Sep. 2012	An automatic voltage reference setting algorithm is employed to optimize the voltage profile in real time based on a distribution state estimator. Simulations demonstrate this algorithm can increase DG output without voltage limits violation.
[33]	Sep. 2012	A comparative study is presented to highlight the effectiveness of EES in power delivery systems. In this work, ESSs aim to minimize the costs of ANM schemes by considering previous BSS operation states and future conditions.
[34]	Sep. 2012	An EA, based on the load shifting technique, defines the optimal DSM. Results prove the effectiveness of the proposed algorithm whereas the peak load is reduced and a large number of electric devices is controlled.
[35]	Nov. 2012	The proposed AROPF formulation is adopted to find out the optimal daily operation schedule of WT-BSS. The usage of a power conditioning system is presented to enable the reactive power dispatch of BSS.
[36]	Nov. 2012	A probabilistic OPF is modified into a deterministic OPF by using the Taguchi orthogonal array testing for selecting the minimum testing scenarios. With the proposed robust OPF, the solution satisfies the most possible scenarios.
[37]	Feb. 2013	The proposed method optimally dispatches the output voltage of DG units that coordinate with OLTC and ShC. The global optimal solution is found, while significant reduction of power losses is achieved considering the stochastic nature of RES.

Table 2 (*Continued*)

Reference	Published	Contribution
[38]	Feb. 2013	A volt/var optimization method, modelled as MILP, is recommended to solve the OOSDN problem by considering the load voltage dependence due to the so called "ZIP load model" (i.e., Z: constant impedance, I: constant current, P: constant power).
[39]	May 2013	A GA defines the optimal operation schedule considering the stochastic nature of PV output, whereas a BSS mathematical model is well-established. This GA approach could be employed for other BSS applications (e.g., load shifting).
[40]	Jun. 2013	The deployment of a decentralized control for the optimal voltage regulation is proposed. Each network agent, firstly, evaluates the power system operation values, and then, optimizes its own design variables by adopting SA.
[41]	Aug. 2013	A DP algorithm optimally schedules the controllable ShCs, OLTC & voltage output of DG units; VSFs and BB method are employed to reduce the computational burden.
[42]	Aug. 2013	Two stage methodology: 1) optimization of the hours of charging and discharging of BSS 2) AROPF, such as in [35]. This paper extends the work of [35], which considers as constant the hours of charging and discharging of BSS.
[43]	Sep. 2013	A decentralized DG control method uses local measurements at the PCC and combines the Kalman filters with the constrained recursive least squares algorithm. Feeder's voltage regulation is achieved by the coordination of DGs with OLTC.
[44]	Dec. 2013	A MPC method exploits the online measurements to avoid the dispensable future manipulation of SDN components. The cheapest SDN components triggered first, whereas the more expensive ones are used when the emergency limits are exceeded.
[45]	Jan. 2014	An OOSDN method is described to mitigate the number of tap changes. This objective is achieved with an efficient PV reactive power dispatch based on one-day-ahead simulation, given the load and solar irradiance forecasting.
[46]	Jan. 2014	A CSP algorithm and an OPF algorithm are deployed Power Flow Management (PFM) in real time. The OPF PFM achieves higher harvest from non-dispatchable DG units than CSP OPF.
[47]	Feb. 2014	A heuristic technique reduces the computational time for real-time reconfiguration by handling RCS via a SCADA system. The performance of the presented technique was evaluated in a real distribution network.
[48]	Mar. 2014	Feeder voltage divergence factor, VUF and voltage cost sensitivity factor are introduced in the OOSDN of both MV and LV networks. Results show that the proposed method can increase the lifespan of BSS equipment.
[49]	Mar. 2014	The performance of a well-established MINLP with rectangular coordinates is compared with a MIQC formulation as in [50], for OOSDN. Both approaches are used for the optimal management of network constraints.
[50]	Jan. 2014	A dynamic OPF formulation for OOSDN considers the inter-temporal variable of state of charge of ESS in an ANM framework.
[51]	Jun. 2014	An alternative power flow approach is proposed for radial distribution networks. The problem, that is a MINLP problem, is transformed into a MIQC programming problem for OOSDN with RCS and DG curtailment for overload management.
[52]	Jun. 2014	This work presents the actively participation of consumer-side using a DR management system considering the uncertainties of wind, solar and demand. DG reserve management is also considered to handle the uncertain scenarios by the DSO.
[53]	Jul. 2014	Two algorithms for CVC are described and compared: a) a rule-based algorithm and b) a mathematically modelled MINLP algorithm.
[54]	Aug. 2014	A mixed integer GA takes into consideration the manipulation of RCS for optimal DG and RL dispatch scheduling. This work introduces the maximum permitted switching operations as constraint.
[55]	Nov. 2014	The insight of proposed two-stage control: the EMS, firstly, defines the optimal day ahead charging/discharging scheduling of BSSs, and after, the BSS set points are sent to local controllers for short-term adjustments (in real time).
[56]	Jan. 2015	A risk-based OPF approach extends a deterministic OPF subject to probabilistic constraints that handle risk considering the uncertain nature of wind.
[57]	Jan. 2015	The presented dynamic reconfiguration coordinates with other ANM schemes to accommodate the higher DG penetration and heal network congestions in real-time. A technique to mitigate the size of the multi-period OPF problem is also proposed.

In [22], for each time interval, a two-stage OPF algorithm, which is formulated as a mixed integer non-linear programming (MINLP), aims at the maximization of total network profit. In the first stage, the problem is treated as NLP (all the design variables being continuous); subsequently, in the second stage, the problem is solved considering the control variable of OLTC to be integer, as it is rounded to the nearest value of the previous step [22]. A similar approach to [22] is executed in [53] with a three-stage procedure. A MINLP formulation is employed for thermal overload management in [51] and for CVC in [49], whereas both papers introduce a transformation of the MINLP problem to a mixed integer quadratic constrained (MIQC) problem. A multi-objective MINLP minimizes costs and gas emissions, in [52]. A MINLP problem is solved in two stages in [42], where the first stage determines the integer variables of charging and discharging time period of BSS and the second stage solves a NLP problem of AROPF as in [35]. A MINLP problem is transformed to NLP, in [23], to mitigate the computational burden by relaxing the discrete variables of OLTC and switched capacitors. In [57], a multi-period OPF is formulated as MINLP to maximize the hosted DG capacity; the authors of [57] extend the works of [10,18] considering RCS for NRM as an ANM scheme.

4.1.4. *Interior point (IP) method*

In [50], a dynamic OPF maximizes the utilization of DGs using the IP method. The primal-dual interior point method is used to minimize the GC and to minimize the tap changing operations in [8,45], respectively. In [55], the IP method solution is used as initial solution to patterns search optimization.

4.1.5. *Quadratic programming (QP)*

A QP problem aims at the minimization of the variations of DG power output and the changes of the OLTC system, in [44], considering the controls that will be applied in the near future.

4.1.6. *Dynamic programming (DP)*

DP is applied to search the optimal schedule for minimizing total cash flow in the studied period [21]. In [5], the optimal OLTC position and the status switched capacitors (on or off) are determined using DP. In [37,41], the OLTC, the voltage output of DG units at PCC and the ShCs are optimized with DP; [41] uses the branch and bound (BB) method and the VSFs.

4.2. *Heuristic methods*

4.2.1. *Genetic algorithm (GA)*

A simple GA is employed for the volt/var control optimization in [1]. A GA is solved to define the optimal operation of SDN equipment such as OLTC, SVR, ShC, ShR and SVC [6]. A mixed integer programming problem is solved by a commonly used binary GA for optimizing the charging/discharging BSS schedule [39]. In [54], a well-structured GA solves the MINLP problem of optimal operation schedule considering DGs, RL and NRM. The matrix real coded GA (MRCGA) that is proposed in [19], determines an optimal operation schedule in order to minimize the operational costs of a microgrid.

4.2.2. *Evolutionary algorithm (EA)*

A multi-objective optimization problem is solved by employing an evolutionary technique using fuzzy sets, while only the mutation operator is used through the evolution [2]. An EA is also proposed in

[34] with a DSM technique for optimal load shifting; the consumers demand behaviour is modelled depending on their lifestyle.

4.2.3. Simulated annealing (SA)

The minimization of the objective functions, addressed in [40], is achieved by adopting SA. The proposed SA-based optimization technique seems to have satisfactory performance in terms of convergence and computational speed for the requirements of solving the distributed consensus problem of network agents.

4.2.4. Practical heuristic algorithms

Two methods for optimal reactive power control and optimal CVC are presented in [26,31], respectively, for a real time implementation; both of these practical methods are based on the empirical estimation of the minimum and the maximum points of voltage profile using the installed remote terminal units (RTUs). An hierarchical control method, based on a flowchart, is employed for ESM and voltage regulation in [29]. A heuristic technique, which is based on the analytic hierarchy process for multi-objective analysis, is used in [47] for analyzing the connection among feeders for the most efficient NRM. In [30], a MINLP problem is solved using a heuristic optimization algorithm adopting the NRM scheme. Authors of [48] propose an algorithm to control the voltage along the feeder by taking advantage of the voltage sensitivity matrix and the actions having the less cost. Both [9,15] outline rule-based algorithms for the optimal usage of ESS, whereas the objective is to meet a preferable output power curve that is used as reference.

4.3. Stochastic methods

The consideration of natural resources uncertainties aims at avoiding or mitigating the risk in the OOSDN. A risk-based OPF algorithm simultaneously maximizes the exploited wind energy and reduces the control actions, in [56]. In [11], a probabilistic power flow (PPF) is proposed considering the uncertainties of the time-varying load and the variable DG output; the PPF is solved with the point estimate method (PEM); the optimal operation of SDN components for voltage control is determined for all the possible network configuration states. In [36], a robust OPF algorithm is proposed to consider the eventual load or RES variation.

5. Challenges and future research

Towards the smart grid era, the key challenge is the upgradability of conventional distribution systems and the further integration of emerging technologies, i.e. AMI, ICT and DMS. However, most utilities still stay passive and they have not fully integrated smart systems and smart equipment. Only few pilot projects have been implemented, and thus, great effort is needed to go beyond. The utilization of cutting-edge technologies and smart systems can facilitate the flexible operation of DGs, BSSs and RES. Although significant investigation has been conducted in the area of smart grids and in the area of OOSDN, there are still interesting fields for future research and areas for further investigation as described in the following sections.

5.1. Comparison between investment in SDN infrastructure and network reinforcement

Smart grid infrastructure and automation in power distribution networks are still assumed to be a costly investment in order to convert the conventional networks into smart distribution systems. However, such an investment might contribute to the deferral of network reinforcement. Hence, DSOs should conduct detailed techno-economic studies of this upgrade and they have to compare them with other alternative solutions, i.e., network reinforcement.

5.2. Cost-benefit comparative analysis of centralized and decentralized control

The selection of smart grid control architecture between a centralized and a decentralized approach specifies the investment cost, the operation cost, the benefits, the technical challenges and the capabilities that occur from the utilization of each approach. Nevertheless, standardization is needed to facilitate the appropriate selection of the control architecture. Consequently, the most economic and efficient control architecture should be selected in accordance with the method that is employed for OOSDN.

5.3. Consideration of forecasting errors in SDN operation

Several works investigate the optimal one-day-ahead operation schedule, and they assume that the predicted load curve and the predicted variable generation curve (e.g., wind and solar power curve) have negligible forecasting errors. As a result, stochastic approaches are needed to consider these forecasting errors. New risk-based OPF techniques should be proposed to cope with uncertain scenarios. The main idea is to optimize current and future control actions taking into account predictions and their probability density function. The model predictive control (MPC) is also a technique that can be further investigated towards this direction, as papers [73,74] already introduce.

5.4. Consideration of AMI accuracy

The real-time operation significantly leans on RTUs and smart metering devices that are installed in the SDN; e.g., in case of centralized control, the decisions made by the DMS for voltage control, are based on the acquired data and how much precise these data are. Potential inaccurate measurements of AMI devices may seriously influence the normal operation of distribution network, whereas they may lead to undesirable situations. Consequently, the inaccuracy of RTUs and/or AMI devices should be considered in the optimization models of OOSDN in terms of reliability.

5.5. Reliability and performance of ICT infrastructure

With the presence of ICT in modern power distribution networks, conventional networks are gradually transformed into smart grids. The smart grid consists of DER controllers and SDN components (e.g., relays, OLTC, inverters, controllers, RTUs, AMI, etc.) that are coordinated by utilizing the integrated ICT. Modern techniques of OOSDN are taking advantage of ICT integration in power systems, but assuming no failures, no data loss and fast response in communication. However, potential failures of ICT and the unexpected interruption of communication might influence the normal operation of SDN and may induce mistaken operation decisions. Moreover, response delays of the installed SDN equipment may imply congestions or non-economic operation. As a result, an interesting subject for future research might be how the performance of ICT can affect the reliable operation of power distribution systems.

5.6. Price elasticity of demand and dynamic pricing

As far as price responsive demand is concerned, energy consumption strongly depends on the time-varying pricing of electricity, but the behaviour of residential consumers has not yet adequately been understood. It is necessary to determine the degree to which end-users change their energy consumption according to dynamic pricing. Yet, such a research requires the broad integration of AMI in consumer-side and a substantial amount of measurements to approximate the behaviour of residential consumer. The open access to the measured data will help researchers to realize the modification of consumer behaviour depending on some criteria, such as region, country, economic and social status, etc. Industrial and commercial consumers have different energy consumption needs and habits, something that should be also considered. As consequent, by including the price elasticity of demand in the dynamic pricing and by composing social-economic studies of consumer response to dynamic pricing, new models and computational tools should be developed and applied to OOSDN.

5.7. Online reconfiguration considering current technical needs

Online reconfiguration is an efficient ANM scheme that intends to reduce the curtailment of DG and facilitates the increment of DG hosting capacity. New models, which would take into account the current technical needs, should be deployed. These technical needs include: (1) the reallocation of DGs among the network feeders affects the fault current level and this could induce problems to the feeder's protection; (2) the fast wear of the RCS is due to their frequent switching operations in the case of high DG penetration; and (3) risk of congestion owing to RES uncertainties and mistaken network topology.

5.8. ESM versus DSM: participation of end-users

ESM and DSM seem to be competitive in terms of investment cost and effectiveness level. The efficiency and the benefits of these two SDN management approaches have been already investigated by the aspect of how DSOs can take advantage of these technologies. Further investigation should be carried out in how end-use customers can participate in these ANM schemes, and a comparison between them may highlight the cases that the one surpasses the other. Dynamic pricing of electricity and BSSs are examples of DSM and ESM, respectively, and e.g., they can be employed for load shifting. Both of these technologies depend on the energy consumption lifestyle of end-users and thus, new researches should be performed in this area. New research papers may consider the integration of ESS in the end-use customer side and consumers behaviour in response to dynamic pricing. The extracted results would be useful in order to select the ANM scheme that best suits in accordance with end-users and their attributes.

5.9. DER and ANM: regulatory framework restructuring

The enduring growth of DG penetration and the variety of different DER technologies, which tend to intensively be interconnected with SDNs in the near future, create challenges and impose competition in the electricity market. Some of the queries, being raised, deal with the following: the priority of DG connection and/or curtailment; how the regulatory framework prevents or allows the participation of DER units in voltage regulation as ancillary services; the structure of tariffs for the optimal operation of DER depending on the operation mode (e.g., steady-state operation, ancillary service, emergency conditions, etc.) Future research might be carried out for defining the regulatory framework that could contribute in the optimal operation of smart grids. Regulators should consider the developed ANM techniques, proposed by research teams (institutes, academia and industry), in order to postpone the costly investments, such as e.g., network expansion, network reinforcement, expensive equipment replacement.

5.10. SDN planning based on ANM and optimal operation

Although several methods for optimal DG placement and power distribution planning have been proposed, more investigation is currently carried out to transform the conventional power networks into smart grids or planning the new smart grids from the beginning. Power engineers and researchers should thoroughly consider the developed methods of OOSDN in order to plan the modern power distribution systems. The implementation of ANM can facilitate the optimal DER siting and sizing and the effective network expansion. The optimization of operation in real time and the optimal daily dispatch scheduling may significantly decrease the costs of SDN planning and could avoid the oversizing of distribution network assets.

6. Conclusion

This paper introduces a taxonomy of the models and the methods that are employed for OOSDN, outlines the ANM schemes and proposes future research in the OOSDN field. Moreover, this paper identifies the main contributions of the reviewed OOSDN works. The most common model for OOSDN consists of: (1) non-dispatchable DG, (2) 24h-curve for load and generation profile, (3) CVC as ANM scheme and (4) centralized control. Different objective functions are classified according to DSO requirements. The methodologies for solving OOSDN problem are classified into three major categories: (1) numerical, (2) heuristic and (3) stochastic methods. The most common approaches for solving the OOSDN optimization problem are the MINLP and the practical heuristic algorithms. The technical challenges and the areas for future research, proposed in this paper, include the consideration of investment in SDN infrastructure; comparative studies of centralized and decentralized control; consideration of forecasting errors in SDN operation; consideration of AMI accuracy; reliability of ICT; price elasticity of demand and dynamic pricing; online reconfiguration considering current technical needs; participation of end-users in ESM and DSM schemes; restructuring of regulatory framework for ANM.

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