Sectionalizing distribution networks concept and system framework

_Citation for published version (APA):_

**DOI:**
10.1109/SEST.2018.8495731

**Document status and date:**
Published: 17/10/2018

**Document Version:**
Accepted manuscript including changes made at the peer-review stage

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

**Link to publication**

**General rights**
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

**Take down policy**
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Sectionalizing Distribution Networks Concept and System Framework

M.H. Roos*, P.H. Nguyen*, J. Morren†, J.G. Slootweg†

*Electrical Engineering
Eindhoven University of Technology,
Eindhoven, the Netherlands
Email: m.h.roos@tue.nl
†Asset Management,
Enexis Netbeheer,
’s-Hertogenbosch, the Netherlands

Abstract—The increasing dependency of society on electricity motivates the research for more reliable and resilient distribution networks. Self-healing of networks is one of the key elements of the Smart Grid concept. Conventional self-healing networks (CSHNs) recover part of the network by rerouting power with automated switchgear. By utilizing microgrids (MGs), the sectionalizing distribution networks (SDNs) concept is an extension of CSHNs, which utilizes both automated switchgear and distributed energy resources (DERs) to create both grid-connected and islanded microgrids (MGs). The SDN concept provides more resilience against faults than CSHNs and allows local bottom-up blackout restoration. This paper provides a high-level conceptual and operation states description, a system framework, and the operational sequence of SDNs in case of faults. Finally, several future research directions are proposed.

Index Terms—sectionalizing distribution networks, microgrids, islanding, self-healing

I. INTRODUCTION

When a fault occurs in a distribution network, it is detected by protection systems which isolate the part of the network containing the fault. The isolated part of the network experiences an outage, which may have a large economical and societal impact [1]. To minimize the impact of outages, distribution network operators (DNOs) aim to restore the supply of the maximum amount of load in minimal time. The ongoing electrification of households, and commercial and industrial processes increases the dependency on electricity and therefore the impact of outages. This increases the need for a reliable electricity grid, motivating research towards more reliable and resilient distribution networks.

The integration of automated switchgear enables DNOs to create self-healing networks which partly restore the supply of load with switching operations [2]. Self-healing networks are part of the “Smart Grid” concept and have been a topic of research for the last years [3]. Conventional self-healing networks (CSHNs) are distribution networks which utilize automated switchgear to supply part of the load after a fault occurs in the network as described by [4]–[6]. CSHNs enable resilience against faults [7], which is the ability of networks to “anticipate, absorb, adapt to and/or rapidly recover from a disruptive event” [8].

There is an ongoing trend of the integration of more distributed energy resources (DERs), automated switchgear, and information and communication technology (ICT) systems into distribution networks. The DERs consist of flexible load (e.g. electric vehicles), energy storage and distributed generation (e.g. photovoltaics). These trends enable the introduction of microgrids (MGs) into distribution networks. Microgrids are considered as a key resource to enhance the resilience of distribution networks [9], due to the high controllability and islanding functionality.

Three concepts can be distinguished which utilize MGs to improve the reliability and resilience of distribution networks. In the first concept, a distribution network consisting of autonomous microgrids is considered. Therefore, part of the role of the DNO is performed by the individual microgrid operators. This concept potentially has a high reliability and resilience due to the high level of automated switchgear and microgrid islanding capabilities. The microgrids may normally operate in either grid-connected or islanded operation. A network of self-adequate microgrids is proposed by [10]. When a loss of generation occurs in a MG, it requests support of other MGs. However it has to rely on other MG owners to be willing to do so. This may require payment of large incentives to the other MG owners. This problem can be solved by the two-level architecture proposed by [11] in which the DNO acts as MG coordinator. However, this requires DNOs to gain access to control all the resources in the MGs which decreases the autonomy of MGs.

In the second concept, one or more MGs are connected to a common distribution network. In case of faults, the MGs support the network by power injection as described by [12], [13]. These sources propose to distinguish between critical and non-critical load in MGs to provide more effective restoration. By taking the uncertainty of renewable energy sources into account, MGs with a generation capacity larger than their critical load can be identified [12]. Only MGs with momentary surplus generation capacity support the distribution

This work has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement N°773717

978-1-5386-5326-5/18/$31.00 © 2018 IEEE
network. This concept is only effective when MGs are located nearby the fault, when MG operators are willing to support the distribution network and when MGs have surplus generation capacity. Similar to the first concept, MG operators can choose to island the MG which prevents the MG from supporting the distribution network.

The third concept is sectionalizing distribution networks (SDNs). SDNs are interconnected distribution networks which can be separated into islanded and grid-connected MGs in case of a fault. Similar to CSHNs, part of the network is restored by rerouting the power with automated switchgear. The part of the network which cannot be restored in this way is sectionalized into islanded MGs. The MGs balance the demand and supply by controlling DERs. This concept grants a potentially high reliability and resilience, depending on the quantity of automated switchgear and DERs available in the network. The integration of SDNs can significantly increase the reliability and resilience of distribution networks, reduce outage costs, and improve the quality of supply [14]. The utilization of the distribution network is shared between all connected parties and operated by the DNO as an independent entity. Therefore, in contrast with the other concepts, it is generally beneficial for all connected parties to support the network in case of a fault.

Although SDNs are promising systems which can effectively increase the reliability and resilience of distribution networks, there is limited literature available. A rolling-horizon control strategy is proposed by [14] to guarantee the supply-demand balance in islanded sections of SDNs. The strategy constructs self-adequate MGs in the faulted area by optimally sectionalizing the network, load shedding and controlling DERs. Secondly, the DERs in the unfaulted network are redispatched.

A system and operation planning framework for SDNs is described by [15]. This framework aims to increase the effectiveness of SDNs by planning the candidate MGs in advance. The candidate MGs which are formed in case of a fault are optimized during system planning and operation planning. In the system planning stage this framework describes how DERs are optimally located among the candidate MGs. In the operation planning stage the DERs are controlled to optimize three properties of the candidate MGs: self-adequacy, energy losses and disconnected load.

To develop interoperable SDN systems and compare different SDNs, a standardized description is required. Comprehensive operational and system descriptions of SDNs are lacking in literature. Without these descriptions, development of interoperable SDN systems and comparison between different SDNs is complicated. This paper aims to fill this gap by giving detailed conceptual, operational and system descriptions of SDNs. Providing a standard for the operation and systems of SDNs, and a method for DNOs and researchers to compare the required systems. This results in the acceleration and increased effectiveness of research and integration of SDNs.

The next section defines a high-level conceptual description of SDNs including objective and operational states. Section III describes a system framework to compare SDN subsystems by giving a system level description, while the operational sequence of SDNs is described in section IV. Finally, conclusions are given and future research is proposed in section V.

II. SECTIONALIZING DISTRIBUTION NETWORK CONCEPT
A. Objective

When an outage occurs in a distribution network, the load in the network is not supplied and the capacity of distributed generation in the network is not utilized until the outage is cleared. Unsupplied load can have a large impact on consumers and has economical consequences for the DNO of the network. Unutilized distributed generation can especially cause problems during islanded operation due to a lack of generation capacity. This can also have environmental impact when renewable generation capacity has to be replaced by fossil generation capacity. Therefore, the objective a SDN is: to optimize the supplied load and utilization of generation capacity in the network during a fault by controlling automated switchgear and DERs.

Since there are different types of loads and generators in the network, this objective can be reached in different ways. The supplied load can be optimized by maximizing the total power or energy supplied. A different approach is a weighted optimization e.g. as described by [12]. In the weighted optimization, critical loads such as hospitals are supplied before the non-critical loads. For generation, the generators with the highest controllability, the lowest cost and the smallest environmental impact may be selected.

B. Operation states

In principal, a network can be categorized into five operation states [16]. An operation states diagram for SDNs is shown in figure 1. When no fault has occurred, the supply-demand
balance for each possible fault is assessed. When the amount of distributed generation capacity is adequate for each considered fault, the SDN is in the "Normal operation" state. When there is not enough generation capacity in the network, the SDN is in the "Alert" state. In this state, preventive control actions e.g. charging of energy storage systems in the network may be taken. If a fault occurs while the network is in "Alert" state, (flexible) load is shed to maintain the generation and load balance. In this case, the network goes into the "Restorative" state.

When the network is in "Normal operation" state while a fault occurs, the network goes into "Emergency" state. In this state all load (including flexible load) is supplied, all DERs are operating and (part of) the network is in islanded operation. The power injection of generating DERs may be curtailed in this state to locally balance generation and load. When the available generation capacity is lower than the load in the islanded part of the network, (flexible) load is shed and the network goes into "Restorative" state. When there is no generation capacity in the network e.g. by depleted energy storage, the network goes into "Blackout" state. If instabilities occur in the network which cause voltage or frequency violations, the network may go into "Blackout" state from either the "Emergency" or "Restorative" states. In this state, blackout recovery is initiated by coordinating recovery of DERs while maintaining the generation and load balance in the network.

C. Resilience in case of faults

From the perspective of a distribution network, faults which can occur either internally or externally. Examples of three SDNs connected to a transmission network before and after three different faults are shown in figure 2. Network D1 experiences an internal fault, leading to sectionalizing of the network. Part D1a remains connected to the transmission network and therefore remains in grid-connected operation. Part D1b is operating in islanded operation, utilizing the local DERs for voltage and frequency control. Networks D2 and D3 experience external faults: a transmission network fault, and a fault in the connection between the transmission network and network D3 respectively. Both networks are in islanded operation after the faults and utilize the local DERs for voltage and frequency control. The tie line between the network is utilized to improve balancing of supply and demand. If either network would experience a blackout while in islanded mode, the network can recover by coordinated control of DERs.

III. SYSTEM FRAMEWORK

This section describes a SDN system framework, the objective of each subsystem in SDNs and the operational sequence in case of a fault. The system framework is based on six subsystems which have to be added or modified in existing distribution networks to enable the SDNs concept. The subsystems are: control system, ICT system, switchgear, DERs, protection system and short-term planning system as shown in figure 3.

A. Short-term planning system

The short-term planning system is not often considered in literature and is the only optional subsystem. When the system is not available, MGs have to be islanded ad-hoc when a fault occurs which may increase the outage time. This system increases the effectiveness of SDNs by optimizing the self-adequacy of islanded MGs for each possible fault. This determines whether SDNs are operating in "Normal operation" or "Alert" state. The planning system aims to have the required amount of DERs capacity available in the network to supply the load in the network after a fault occurs. The required DERs capacity depends on the forecasted load in the network. The planning system distinguishes between critical and non-critical load. To reduce interference with normal network operation, generation capacity is only provisioned for critical load.
B. Control system

The control system in SDNs has several tasks, which are usually divided over multiple devices in the network. To enable optimal operation of MGs in both grid-connected and islanded modes, a hierarchical control structure is usually utilized [17]. This structure consists of primary control, secondary and tertiary control, each acting on different timescales.

Primary control can be divided into inner control and power sharing control. When multiple DERs are present in a network, they can operate in grid-feeding or grid-supporting mode. Grid-feeding DERs only have inner control to control the current and power injected to the grid. Grid-supporting DERs have inner control to control the current, voltage and frequency, and power sharing control to divide the load in the network between different DERs [18]. The inner control is decentralized and located at each DER to provide current, voltage and frequency control. The power sharing control provides power sharing between DERs and "plug and play" capability. Secondary control compensates the voltage and frequency deviations from nominal caused by primary control, and optimizes the DERs for economical operation. The tertiary optimizes the power flow from and to the MG for economical operation [17].

To enable SDNs, this paper proposes to add restorative control to this structure. Restorative control operates the automated switchgear in the network to sectionalize SDNs in case of a fault. After sectionalizing, restorative control, sheds load in case of a generation deficiency, controls the injected and absorbed power of DERs, and coordinates DERs during blackout recovery. This system therefore controls the transition between "Blackout", "Restorative" and "Emergency" states.

C. ICT system

The ICT system enables communication between the other subsystems, and provides processing power for calculations and the processing of data. The subsystems are divided over different locations such as households, electric vehicle charging stations and substations which requires several different communication technologies to be used [19]. The ICT system should therefore be able to utilize different communication technologies, while delivering fast and reliable service. Since the operations such as balancing of power within islanded MGs are time critical, the reliability of SDNs is directly linked with the reliability of the ICT systems.

D. Switchgear

The SDNs concept can only be implemented in networks with automated switchgear. Automated switchgear is utilized to sectionalize the network in case of a fault and switch tie lines between MGs to enable power flow between islanded MGs. The capabilities of each switch is determined by the type of switchgear. Circuit breakers can switch high (fault) currents, load-break switches can switch load currents and isolators can only switch when no current is flowing. Several switching actions are performed during the operation of SDNs, for effective operation these actions have to be performed in the optimal sequence, at the optimal locations and with a suitable type of switchgear.

E. Distributed energy resources

The DERs in SDNs should provide power generation, energy storage capability and flexible load capacity to maintain the supply-demand balance during islanded operation. To enable the bottom-up blackout restoration capabilities of SDNs, a black start capable generator should be present in the network. Conventionally, islanding of DERs after a fault is prevented by anti-islanding protection and the limited fault ride-through capabilities of DERs. However due to the recognized advantages of fault ride-through and islanded operation, recent standards allow DERs to remain operational during islanding and prescribe larger voltage and frequency ride-through capabilities [20].

F. Protection system

The protection system should accurately detect and isolate faults in the network to prevent damage to network components. To prevent disconnection of DERs in the network, the fault should be isolated within the fault ride-through time of the DERs. If DERs disconnect after a fault occurred the amount of resources to maintain the supply-demand balance in the islanded MGs are reduced, decreasing the effectiveness of SDNs. To improve the fault ride-through of DERs, fault current limiters may be used as described by [21].

The network topology of SDNs is dynamic due to the reconfguration and islanding capabilities. Therefore, the protection system should be able to detect changes in network topology and adapt protection settings. When switching to islanded operation, the timing of the fault isolation and islanding of MGs should be coordinated to optimize performance.
IV. OPERATIONAL SEQUENCE OF SDNS

The operation of SDNs requires several sequential actions to be performed by the subsystems described in section III. A universal modeling language (UML) sequence diagram of these actions is shown in figure 4. For readability, the ICT system is not included in the figure, and primary control is decentralized and included in the DERs subsystem. Communication is available between all subsystems, and communication and data processing is performed at each individual subsystem. The control system performs secondary and restorative control and is assumed to be a centralized controller. Circuit breakers are included in the protection system.

A. Pre-fault

During normal operation of the network, the short-term planning system determines the optimal self-adequate MGs, switching actions and load shedding actions for each possible fault in SDNs. The optimal MGs can be determined by utilizing the planning methodology described by [15]. The switching and control actions are combined to create restoration strategies for each fault, which are sent to the control system at a predefined interval.

B. Fault detection

After a fault occurred in a SDN, the protection system detects and localizes the fault. The fault location is sent to the control system to select the corresponding restoration strategy. The DERs in the network have to ride-through the fault and remain operational.

C. Fault isolation and islanding

After detection of the fault, two switching operations are performed: fault isolation by the protection system and MG islanding. The control system sends switching signals to the automated switchgear to island MGs, and the protection system isolates the fault with circuit breakers. Depending on the location of the fault and type of switchgear available, either the fault is isolated first or MGs are islanded first.

After islanding and fault isolation, the power supply is rerouted via backup feeders or shifting normally open points, and tielines between MGs are enabled. A methodology to perform these operations is described by [5]. The control system sends a signal to the protection system to adapt the protection regime to the new situation. A methodology for adaptive protection suitable to change protection settings is proposed by [22]. The control system also sends signals to DERs in islanded MGs to switch the operation mode from grid-feeding to grid-supporting mode.

D. Islanded operation

During (partly) islanded operation of SDNs, the injected or absorbed power of DERs in islanded MGs are directly controlled by the control system. The control system determines the optimal control strategy to supply the load in the network with a predefined interval. When using the methodology described by [12], non-critical load in the network is shed to optimize the restoration of critical load.

E. Blackout recovery

During islanded operation, a blackout might occur due to instabilities or a (temporary) lack of generation capacity from renewable energy sources. After a blackout, the control system determines the optimal recovery sequence to recover voltage and frequency to nominal values, and balance supply and demand in the MG. The first DER to recover is determined based on the available black-start capable sources and properties such as power rating. The control system sequentially sends recovery signals to DERs, which send signals back to the
when they are fully operational. A methodology to perform blackout recovery is described by [23].

F. Resynchronization and reconnection

When the fault in the network is restored, the islanded MGs are reconnected with the main grid. Before the MGs can be reconnected, the frequency and phase angle of the voltage in each MG should be synchronized with the voltage of the main grid. The control system directly controls the DERs to perform the synchronization. After synchronization, the control system sends switching signals to automated switchgear to reconnect MGs to the main grid. Finally when the network topology of the SDN is restored, the control system sends signals to DERs to operate in grid-feeding mode and the protection system to adapt the protection regime.

V. CONCLUSION AND FUTURE RESEARCH

Sectionalizing distribution networks could significantly increase the reliability and resilience of future distribution networks. However, the SDNs concept has not been well described in literature. This paper describes the objective and operation states of SDNs, a system framework consisting of six subsystems and the operational sequence of SDNs in case of a fault. This provides a standard for the SDNs concept and a system description for DNOs and researchers to compare SDNs and its subsystems. Such a standard will improve the development of future systems and methodologies in the context of SDNs, and increase the effectiveness and integration of SDNs.

Although the SDNs concept is promising, there are several challenges which should be addressed in future research before it can be effectively integrated in existing distribution networks. Some of these challenges are:

- improving the transient stability of DERs;
- optimization of switchgear locations;
- developing suitable and accurate protection systems for SDNs;
- validating the SDNs concept with case studies;
- improving the interoperability between the subsystems mentioned in section III;
- quantitative analysis of the costs and benefits of SDNs;
- addressing cyber security concerns in smart grids.

The first four points will be addressed by the authors in future research.

REFERENCES