DC Soft Open Points for Resilient and Reconfigurable DC Distribution Networks

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Abstract: This paper introduces the concept, theory of operation and applications of soft open points for direct current networks (DCSOPs). The DCSOP is based on a bidirectional DC–DC converter actively controlled to behave like a normal conductor. Unlike the normal conductor, the DCSOP can transfer the electric power between nodes at different voltage levels. With this advantage, the DCSOP can effectively control the power flow direction. Thus, DCSOPs can play a vital role in the reconfiguration of DC distribution networks. The operation and control of the DCSOP device was investigated, both in transient and steady-state conditions. Then, a DCSOP was integrated into a DC microgrid model to validate its ability to change the power flow through the modelled feeders. In addition, a set of reliability indicators was calculated for the DC microgrid under different reconfiguration scenarios. It was shown that reliability is improved when the DCSOP device implements network reconfiguration. Finally, an agent-based framework for controlling the DCSOP in a DC microgrid is presented. A fundamental implementation was created for reconfiguring a DC microgrid with a DCSOP controlled by an agent, proving that the agent-based system can effectively control the DCSOP device for reconfiguration and voltage regulation.

1. Introduction

1.1. Need for DC Network Reconfiguration

Network reconfiguration can be achieved with normally open points (NOPs), which are network connections that are deliberately left open, unless they are required. These can be operated manually or using automation, and they can include different isolation mechanisms. The concept of soft open points/soft normally open points (SOPs/SNOPs) is a subset of the NOP where the connection is facilitated by power electronics. The usefulness of SOPs in distribution networks has been demonstrated in the literature. The literature on soft open points and new power electronics technology for improving the resilience of electrical distribution systems in the future is comprehensively reviewed in [1]. They can be implemented as active network management (ANM) tools, helping to keep parameters such as voltage within statutory and operational limits [2]. Consequently, SOPs can also be used for targeted improvements in network operation, such that distributed generation (DG) penetration is maximised [3]. Other benefits that can be gained by using SOPs include improved feeder load balancing and the minimisation of power losses [4–6]. The majority of the benefits stem purely from the fact that the networks are reconfigured [7]. However, as shown in [4], existing network reconfiguration techniques on their own were not as effective as they were when combined with the utilisation of SOPs. When SOPs are employed, care must be taken to ensure that feeder automation and protection coordination are not adversely affected, although SOPs can potentially help with identification of faults [8,9]. In AC systems, SOPs can be modelled either as a back-to-back (B2B) voltage source converters

(VSC), or as a unified power flow controller (UPFC) [10]. These AC SOP models are characterised by their ability to control reactive power, which is a key consideration in AC network operation.

On the other hand, DC networks do not have reactive power control requirements, but other parameters become more influential, such as voltage levels. The control of multi-terminal DC systems can be more difficult than their AC counterparts, precisely due to the lack of reactive power capability. This becomes especially important during disturbances [11].

DC network studies have been dominated by high-voltage direct current (HVDC) transmission, but hybrid AC/DC systems can also be employed at the medium voltage (MV) distribution level [12]. The benefits of DC distribution, especially at the low voltage (LV) level, have been demonstrated in the literature. One of the key potential benefits is the minimisation of power losses [13], especially at the household level, by avoiding unnecessary AC/DC conversion [14]. Other benefits of using DC distribution systems have been thoroughly researched and demonstrated in the literature [15,16]. In comparison to AC systems, DC distribution systems have lower harmonic content. This benefit is becoming clear with the widespread installation of electric vehicle-charging stations [17,18]. Furthermore, DC distribution systems integrate easily with a wide range of energy storage systems (ESS) and renewable energy sources (RES) [19]. In addition, because of the ease of deployment of energy storage and capacitors, they can provide better dynamic behaviour with the ability to supply pulsed power loads, which improves resiliency and ride-through capability in the event of blackouts and major disturbances in the AC grid. The practical viability of DC networks is a complex aspect, and one of the key considerations is stability, which has different characteristics in AC and DC networks [20].

Multi-terminal SOPs can be employed to help with feeder load balancing in AC systems [12], which indicates the potential for this method to also support DC network stability. The dominant models of AC SOPs require rectification and inversion of the AC waveform through a DC link. In a DC system, this requirement is not there; hence, AC/DC or DC/AC conversion is redundant. Still, there is a need to implement appropriate controls to maintain the benefits of SOPs in a DC system, as opposed to a much simpler automated switch such as a normally open point (NOP).

1.2. Reliability Assessment of Reconfigurable DC Microgrids

The reliability of electricity distribution networks is a very important part of power system planning. A number of methodologies are being used to assess reliability. These mainly relate to reliability indices. The earliest methods have been implemented using probabilistic methodologies, such as Monte Carlo [21]. Test systems have also been put together to aid the development of further, more advanced methods [22]. Reliability assessment is inherently a risk assessment exercise and is based on probabilities of faults and other things that can go wrong. They are a measure of the vulnerability of the power system to potential threats [23,24]. The aim of the reliability assessment is to evaluate the adequacy of the system to supply the load, as well as the security of that supply. To that end, there are numerous reliability indicator metrics that are used in the industry, which are both deterministic and probabilistic. These include, amongst others [23,24]:

- Loss of load expectation (LOLE),
- Loss of load probability (LOLP),
- Expected energy not supplied (EENS),
- System average interruption frequency index (SAIFI),
- Customer average interruption frequency index (CAIFI),
- System average interruption duration index (SAIDI),
- Customer average interruption duration index (CAIDI).

Other indicators can include cost-based assessment, such as the value of lost load (VOLL) [24]. In that case, the impact of the lack of reliability on the operational cost is quantified.

Reliability methodologies have been used widely in the power industry. In the UK, the Energy Networks Association (ENA) provides a number of documents, the most relevant of which are the Engineering Recommendation P2.7 [25], as well as the associated Engineering Reports 130 and 131 [26,27]. These reliability standards are considered very important for the development of future electricity networks, especially considering the challenges that are presented by the development of power systems and the increasing number of threats, such as climate change and cybersecurity [28].

The use of direct current (DC) networks instead of alternating current (AC) networks for electricity has mostly been employed in high voltage transmission, via high-voltage DC (HVDC) systems. The reliability analysis of such systems can be performed using the same indicators, such as SAIFI, SAIDI, CAIDI and EENS [29].

However, low-voltage distribution networks are more complex and can be analysed locally. The hybrid usage of AC and DC distribution networks has been considered in [30,31], and the benefits have been quantified. The authors of [31,32] also considered the concept of microgrids, which is a local segment of the distribution network, and considered the most reliable topologies. The local generation located in microgrids can potentially be used to improve the adequacy and security of the supply. Another important consideration is that the reliability of power systems depends on the reliability of its constituent components. It has been found that some of the weakest points in a local distribution network with power electronics are the capacitors and the power electronic switches [33]. On the other hand, replacing power electronics more frequently means that the implementation of the solutions is updated in accordance with technological innovations.

Finally, the topology and connections of a small network can significantly affect its reliability. Relevant methods have been developed in the past, in order to assess the reliability of a network based on its structure [34,35]. In such methods, the network is segmented and the reliability indices are calculated based on these segments. This is important when considering the reconfiguration of the network, as has been shown in [36,37].

1.3. Agent-Based Control of Reconfigurable DC Microgrids

Multi-agent systems have emerged from the field of computer science and have found widespread application in the area of Smart Grids. Agent-based systems have been proposed for a number of applications in power systems. The first widely recognised attempt to utilise agent-based concepts in microgrids involved the coordination and control of distributed energy resources (DER) [38]. Since then, a series of concepts, approaches and typical applications on power systems has been put forward [39].

The use of multi-agent systems has since extended to the implementation of emissions control in virtual power plants (VPP) [40], as well as the control of electric vehicle (EV) charging, discharging and aggregation [41]. A methodology has also been proposed for developing a multi-agent system that is capable of coordinating resources across multiple energy carriers, such as electricity, gas and heat [42].

However, power systems also require control beyond the coordination of the interconnected energy resources, such as real-time operational parameters. In a microgrid, the control of current, voltage and power flow in real time is vital to its stable operation. Hence, agent-based systems have been proposed for the real-time control of microgrids, also focusing on microgrids where a DC bus is present [43].

Looking at wider system impacts, the use of agent-based technology has been proposed even earlier, in the field of cascading failures and self-healing networks [44]. This approach implies the use of agents who are able to detect an adverse event, assess the vulnerability of the system, and reconfigure and be in charge of the restoration of the system [45]. This is a high-level approach that may lead to an autonomous self-healing network [46].

In terms of DC networks, since these are not widespread, their study is more limited. Still, there have been several propositions for the use of agent-based systems. One of

these concerns hybrid medium-voltage AC/DC networks, where the agents are used to support the frequency of the AC system and allow the interconnection of weak and strong grids [47]. Hybrid AC/DC systems with energy storage have also been considered, where a multi-agent system implements an event-driven microgrid control management methodology [48].

Agent-based systems have also been employed in purely DC networks for controlling heterogeneous storage devices, such as super-capacitors, where limited communications were required [49]. Supervisory control was also implemented using agents in isolated microgrids [50]. Several techniques have been employed for the simulated study of such DC microgrids, such as hardware-in-the-loop (HiL) [51]. In the latter case, the benefits of DC microgrids in terms of demand response have also been quantified.

Finally, one key application of multi-agent systems in DC microgrids is for regulating the voltage and contributing to its real-time operation [52,53]. This is especially important because voltage control in DC networks is slightly more complicated than in AC networks due to the lack of reactive power.

1.4. Contributions to Knowledge

In order to address the need for DCSOP control, this research proposes a design for a DCSOP, based on the model of a virtual conductor that has been introduced by the authors in previous research [54,55]. The main contribution of this paper is the definition of the DCSOP as a bidirectional DC/DC power electronics converter that behaves like a normal conductor. It is proposed as a fundamental component for power routing in DC networks, since it can transfer power between nodes at different voltage levels. In turn, it allows connecting two normally open points in the DC distribution networks; hence, the DC network becomes flexible and reconfigurable.

In order to further investigate the value of DC network reconfiguration with DCSOPs, the segmentation methodologies mentioned in Section 1.2 are employed to study the reliability of a DC microgrid under different reconfiguration scenarios. This provides a system-wide benefit assessment of the DCSOP reconfiguration technology.

The third major contribution of this paper is proposing an agent-based framework for controlling the DC network reconfiguration devices based on signals and measurements taken across the network. This extends the benefits of active network management (ANM) to the field of DC networks.

2. Materials and Methods

2.1. DC Soft Open Point (DCSOP)

2.1.1. Implementation of the DCSOP Using a Bi-Directional DC–DC Converter

The DCSOP is based on the virtual conductor (VC) design. This virtual conductor is technically a bidirectional DC–DC converter with a specific control strategy, as shown in Figures 1 and 2. The main target of this control strategy is to keep the voltage difference between the converter terminals constant at a certain value. Since DC power flow can be controlled through voltage differences between two buses, the ability of the DCSOP to control voltage can be utilised to control power flows. Thus, this VC can play a vital role as a DCSOP in DC distribution networks, since it can connect two normally open points as shown in in Figure 3. The DCSOP can be implemented based on two power electronic circuit topologies, isolated or non-isolated, as shown in Figures 4 and 5. Employing the isolated topology can offer the advantage of electrical isolation between the two normally open points. However, the electrical power is still transferred between them via the DCSOP.
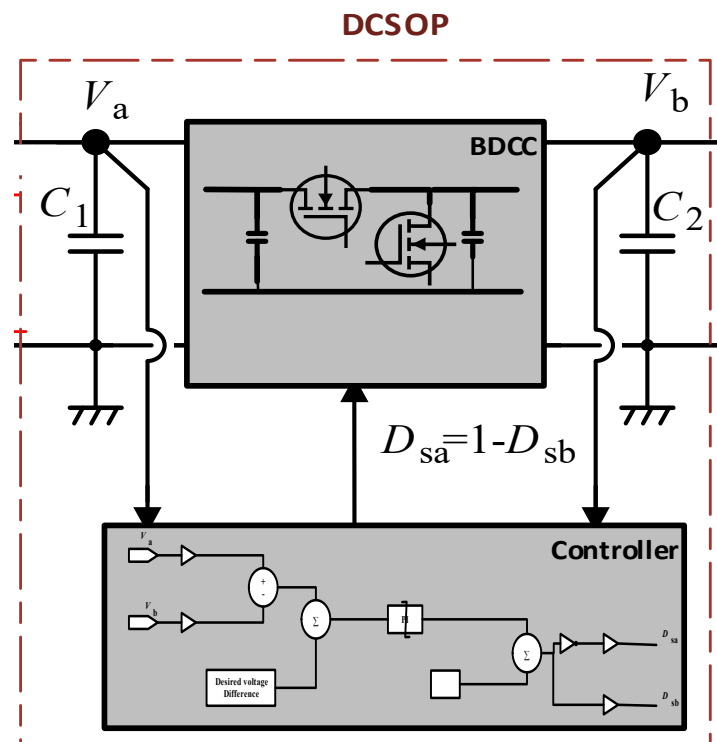
DCSOP

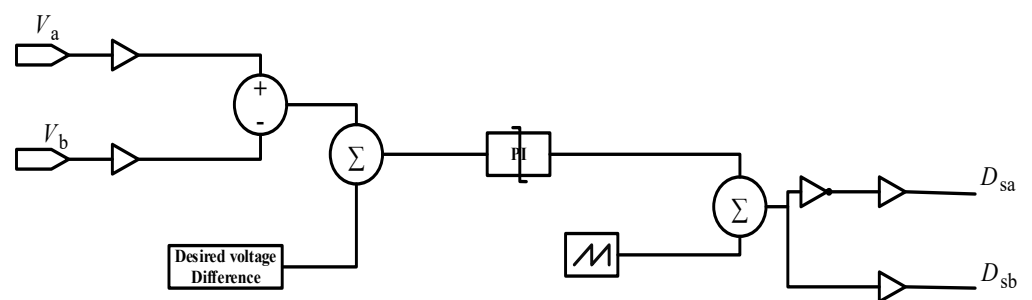**Figure 1.** DCSOP based the virtual conductor.

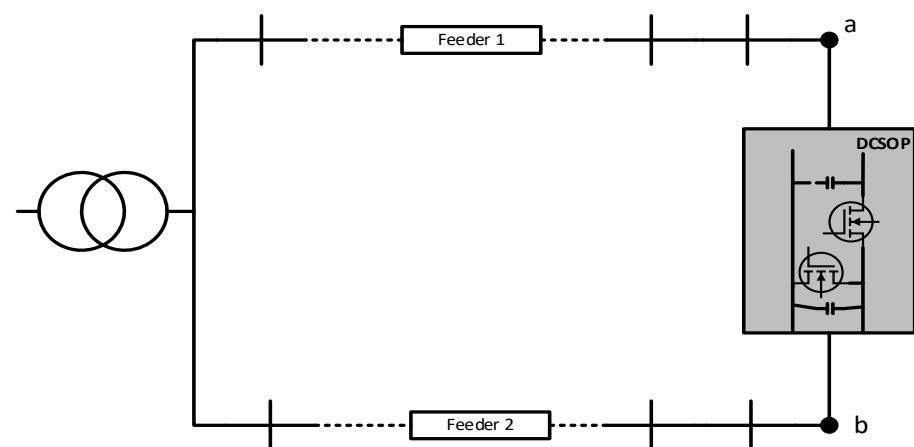**Figure 2.** Control block diagram of the DCSOP.

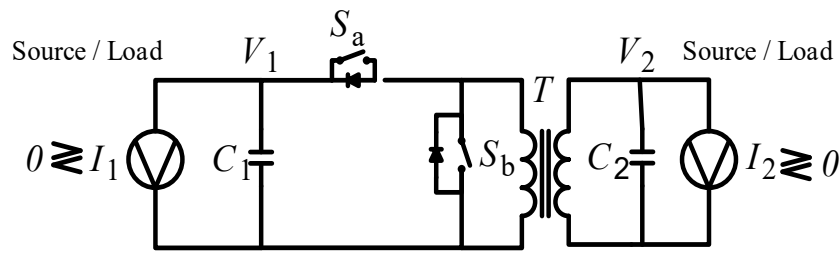**Figure 3.** Basic configuration of a distribution network with a DCSOP.

Figure 4. Main circuit topology: isolated bi-directional DC–DC converter based DCSOP.
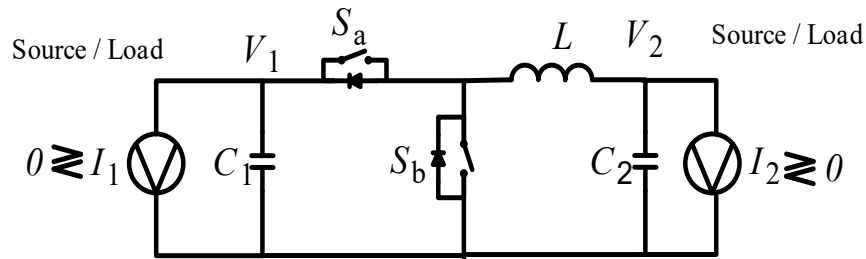

Figure 5. Main circuit topology: non-isolated bi-directional DC–DC converter based DCSOP.

2.1.2. Seamless Averaged Model for the DCSOP

The fundamental bi-directional DC–DC circuit configuration of the DCSOP is as shown in Figure 6. It employs a DC–DC converter to connect two different load/supply units. This model has been implemented in the case study simulations in Section 3 below. The voltage difference between the converter sides is controlled by the duty ratio of the main switch (S_a) and of the complementary switch (S_b). The two bidirectional DC current sources, I_1 and I_2, have internal resistances, r_i and r_o, respectively. There are three storage components: C_1, C_2 and L.
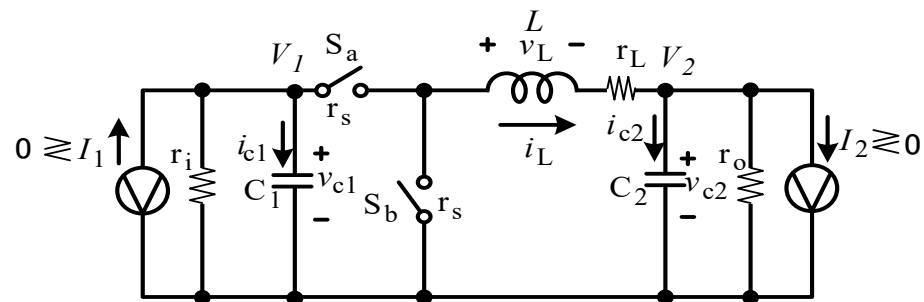

Figure 6. Circuit configuration of the proposed bi-directional DC–DC converter based DCSOP.

The inductor parasitic resistance r_l and the MOSFET turn-on resistance r_s are included in the model. The transfer function for this converter has been derived based on the state-space averaging method. Considering the state-space vector $(t) = \begin{bmatrix} v_{c1}(t) & v_{c2}(t) & i_L(t) \end{bmatrix}$, and the input vector $u = \begin{bmatrix} I_1 & I_2 \end{bmatrix}$; the state-space averaged DC model is shown in (1):

$$0 = A \begin{bmatrix} I_L \\ V_1 \\ V_2 \end{bmatrix} + B \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{1}$$

where:

$$A = \begin{bmatrix} -\frac{r_s + r_l}{L} & \frac{D}{L} & -\frac{1}{L} \\ -\frac{D}{C_1} & -\frac{1}{r_i C_1} & 0 \\ \frac{1}{C_2} & 0 & -\frac{1}{r_o C_2} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ \frac{1}{C_1} & 0 \\ 0 & \frac{-1}{C_2} \end{bmatrix}$$

By solving (1), the following expressions are given:

$$I_L = \frac{r_i D I_1 + r_o I_2}{r_i D^2 + r_o + r_l + r_s} \tag{2}$$

$$V_1 = \frac{r_i I_1 (r_o + r_l + r_s) - D r_o r_i I_2}{r_i D^2 + r_o + r_l + r_s} \tag{3}$$

$$V_2 = \frac{D r_o r_i (I_1 - D I_2) - r_o (r_l + r_s) I_2}{r_i D^2 + r_o + r_l + r_s} \tag{4}$$

where D is the duty cycle.

The state-space averaged AC model is shown in (5).

$$\frac{d}{dt}\begin{vmatrix} \hat{i}_L \\ \hat{v}_1 \\ \hat{v}_2 \end{vmatrix} = A \cdot \begin{vmatrix} \hat{i}_L \\ \hat{v}_1 \\ \hat{v}_2 \end{vmatrix} + C \cdot \begin{vmatrix} I_L \\ V_1 \\ V_2 \end{vmatrix} \cdot \hat{d} \tag{5}$$

where:

$$A = \begin{bmatrix} -\frac{r_s + r_l}{L} & \frac{D}{L} & -\frac{1}{L} \\ -\frac{D}{C_1} & -\frac{1}{r_i C_1} & 0 \\ \frac{1}{C_2} & 0 & -\frac{1}{r_o C_2} \end{bmatrix}, \quad C = \begin{bmatrix} 0 & \frac{1}{L} & 0 \\ -\frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

By solving (5), the following Equations (6)–(8) are obtained:

$$\frac{\hat{v}_1}{\hat{d}} = \frac{-\frac{D}{C_1} \cdot \frac{\hat{i}_L}{\hat{d}} - \frac{1}{C_1} \cdot I_L}{s + \frac{1}{C_1 \cdot r_i}} \tag{6}$$

$$\frac{\hat{v}_2}{\hat{d}} = \frac{\frac{1}{C_2}}{s + \frac{1}{C_2 \cdot r_o}} \cdot \frac{\hat{i}_L}{\hat{d}} \tag{7}$$

$$\frac{\hat{i}_L}{\hat{d}} = \frac{\left(s + \frac{1}{C_1 \cdot r_i}\right) \cdot \left(s + \frac{1}{C_2 \cdot r_0}\right) \frac{V_1}{L} - \frac{D \cdot I_L}{C_1 L} \cdot \left(s + \frac{1}{C_2 \cdot r_o}\right)}{\left(s + \frac{r_l + r_s}{L}\right) \cdot \left(s + \frac{1}{C_1 \cdot r_i}\right) \cdot \left(s + \frac{1}{C_2 \cdot r_o}\right) + \frac{D^2 \left(s + \frac{1}{C_2 \cdot r_o}\right)}{L \cdot C_1} + \frac{\left(s + \frac{1}{C_1 \cdot r_i}\right)}{L \cdot C_2}} \tag{8}$$

Using Equations (6)–(8), the control-to-voltage difference transfer function $G_{d\partial v}(s)$ can be obtained as in Equation (9), where $\partial \hat{v} = \hat{v}_1 - \hat{v}_2$.

$$G_{d\partial v}(s) = \frac{\hat{v}_1 - \hat{v}_2}{\hat{d}} = \left[\frac{\frac{-D}{C_1}}{\left(s + \frac{1}{C_1 r_i}\right)} - \frac{\frac{1}{C_2}}{\left(s + \frac{1}{C_2 r_o}\right)} \right] \cdot \frac{\hat{i}_L}{\hat{d}} - \frac{\frac{I_L}{C_1}}{\left(s + \frac{1}{C_1 r_i}\right)} \tag{9}$$

2.2. Reliability Assessment Method

2.2.1. Reliability Analysis Sets

This work applies a reliability assessment method that was developed by the authors of [34] and also used in [35], in order to study the effect of DC network reconfiguration using DCSOP on reliability. Reliability indices have been examined under different reconfiguration scenarios to quantitatively evaluate the impact of these scenarios.

The reliability assessment methodology is based on the concept of segmentation, where the power system is split into segments. These segments are assumed to be representative of protection systems and their potential to disconnect and isolate sections of the power system during fault conditions.

The method is simple and straightforward, and does not require specialised computer models to be created. In the case of the small network that this paper describes, the calculations are simple enough to be performed manually.

This section describes the sets required to analyse the reliability of a certain load node. The links between these sets are described in Figure 7.
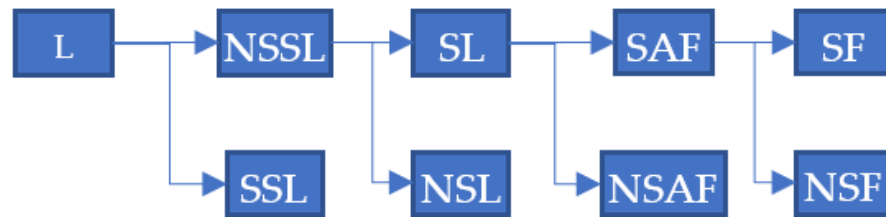

Figure 7. Reliability analysis sets as described in [29].

The "S" segment is defined as the load node that is interrupted.

The "L" set contains all segments of the network, which may cause loss of power to segment "S" if they fail. The "L" set can be divided into subsets "SSL" and "NSSL".

The "SSL" set is defined with respect to a continuous power route between segment "S" and the power source node. It comprises those segments that can be isolated from the above route. In contrast, the "NSSL" set contains these segments that cannot be isolated, i.e., that are integral to the power route between segment "S" and the source. "NSSL" can also be divided into subsets "SL" and "NSL".

The "SL" set contains components that are not integral to supply of segment "S", which can be supplied in another way in case of a disconnection in the "SL" subset. Conversely, the "NSL" subset contains components that are integral to the supply of segment "S" and should not be removed. "SL" is further divided into the "SAF" and "NSAF" subsets.

The "SAF" and "NSAF" subsets are very similar to "SL" and "NSL", although in this case, they refer to the failure of components rather than their removal, and the temporary restoration of supply to "S".

Finally, the "SAF" set is divided into subsets "SF and "NSF". In this case, these sets refer to the restoration of power to segment "S" without violating the system constraints.

Another important parameter that is defined is the downtime for segment "S", referred to as DTs, and given by Equation (10) [35]:

$$DTs = \sum_{\substack{i \in NSL \\ NSAF \\ NSS}} FR_i \cdot REP_i + \sum_{\substack{i \in SSL \\ SF}} FR_i \cdot SOT_i \tag{10}$$

where:

FR_i: failure rate for segment "i".

REP_i : repair time for segment "i".

SOT_i : switch operation time to re-supply segment "S" because of the failure of segment "i".

2.2.2. Reliability Indices

The above downtime calculation was used in the reliability indices below as a measure of the "sum of customer interruption durations". The following two reliability indices have been evaluated during this study [23,24]:

- SAIDI (system average interruption period index) is the average interruption period per customer served.

$$SAIDI = \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customers} \tag{11}$$

- CAIDI (customer average interruption period index) is the average interruption period for those customers interrupted during a year.

$$CAIDI = \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customer\ interruptions} \tag{12}$$

2.3. Agent-Based Model

This section describes the agent-based model that was developed for the purpose of proving the concept of agent-based control of DCSOP within a DC microgrid. The types of agents considered were the microgrid/network agent, the DCSOP agent and the generator/load agent. These are described below.

2.3.1. Microgrid/Network Agent

The microgrid agent is defined as the overarching agent, which has the following capabilities:

- Calculate power flows and operational parameters based on the different measurement points in the microgrid/network.
- Communicate with DCSOP agents and other agents, and provide information and knowledge gained from overseeing the operation of the network.
- Send direct requests to particular equipment agents to act in specific ways.
- Communicate with other DCSOP, load, power flow or other network agents in order to establish joint decision making.
- Communicate with other, adjacent microgrid agents, in case there is any synergy that can be gained, such as load reduction to prevent load shedding.

2.3.2. DCSOP Agent

The DCSOP agent is defined as an agent that has the following capabilities:

- Communicates with other agents (e.g., load agents) and receives messages from them on various conditions in the network.
- Makes decisions regarding the state of the network and whether there is a need to act or not.
- Communicates with other DCSOP, load, power flow or other network agents in order to establish joint decision making.
- Sends commands to the DCSOP device, enabling it to transition from the ON to the OFF state, and vice versa.
- Receives measurements on different parameters from the DCSOP in order to check on the state of the device.

2.3.3. Generator/Load Agent

The generator/load agent is defined as an agent that has the following capabilities:

- Communicates with other agents (e.g., DCSOP or microgrid agents) and sends messages to them regarding various parameters associated with their generator or load.
- Makes decisions regarding the local state of the network and whether there is a need to act or not (e.g., generator disconnection, load shedding).
- Communicates with other DCSOP, load, power flow or other network agents in order to establish joint decision making.

2.3.4. Multi-Agent System Structure

The structure of the multi-agent system including the agents described above is shown in Figure 8.
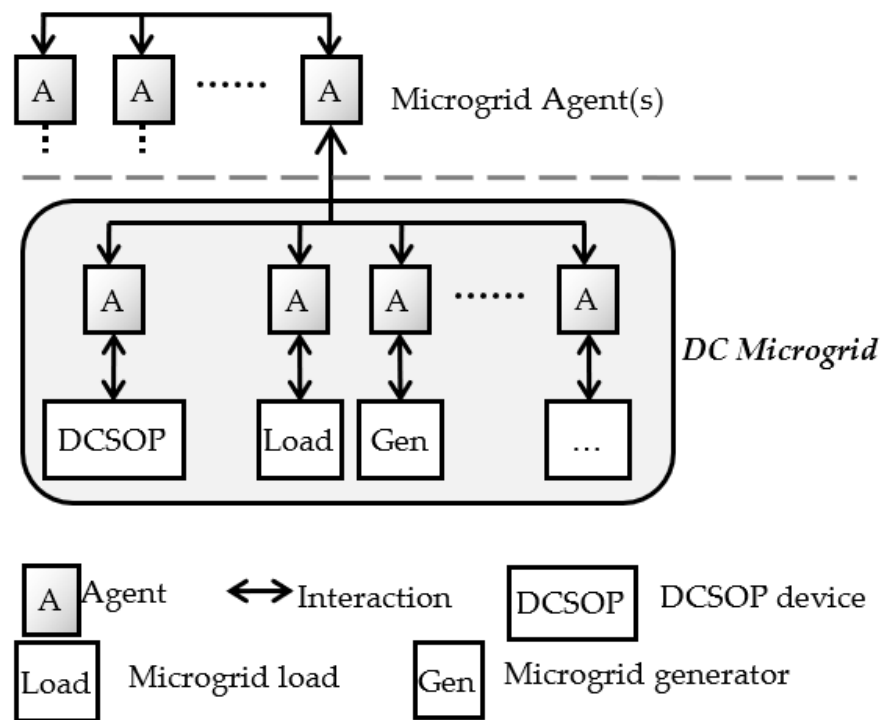
Figure 8. DCSOP multi-agent system structure.

2.3.5. Agent Implementation in MATLAB/Simulink Stateflow

The DCSOP and load agents were implemented in the Stateflow programming environment of MATLAB/Simulink. Screenshots of the implementations that were tested in this work are shown in Figure 9. The implementation was minimal and enabled us to test the concept of controlling the DCSOP within the context of a DC microgrid.
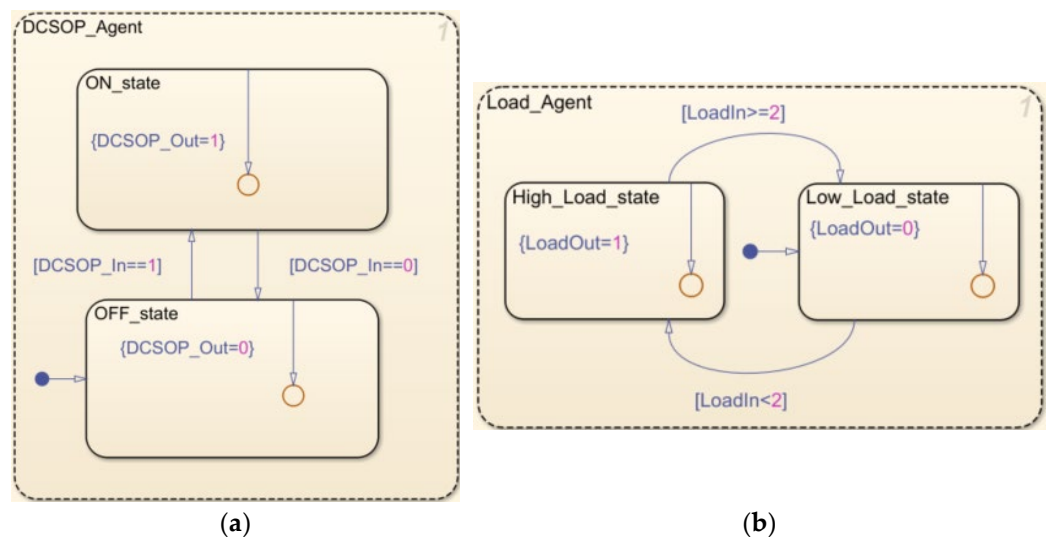

Figure 9. DCSOP agent (**a**) and load agent (**b**) implementation in Stateflow.

The load agent is able to measure the level of the load at a particular point and decide on the classification (low/high). It then transmits the classification to the DCSOP agent.

The DCSOP agent receives the classification of the load from the load agent. If the load is classified as low, the DCSOP agent decides to transition the DCSOP device to OFF, i.e., to open the circuit. If the load is classified as high, the DCSOP agent decides to transition the DCSOP device to the ON state, i.e., to close the circuit.

3. Results and Discussion

3.1. DCSOP Characterisation Case Studies

In order to investigate the performance of the DCSOP, four cases were analysed in MATLAB/Simulink, as shown in Table 1. The first case was the stress test, in which the DCSOP was tested for a very stiff change in the direction of the power flow to ensure a rigid and reliable controller performance. The second case was to test the ability of the DCSOP to control the direction of the current/power flow through the network. In the third case, DCSOP was integrated into a DC microgrid to show its effect on the power distribution through the microgrid. The last case replaced the NOP in the microgrid of the previous case with a short circuit in order to compare its effect with that of the DCSOP.

Table 1. Rationale behind the set of case studies used for evaluating DCSOP operation.

DCSOP Operation Case Study	Rationale
(C.1) Stress test	Evaluate controller performance
(C.2) Control of power flow	Assess the ability of the controller to regulate power flow
(C.3) DCSOP in a microgrid	Simulate the effect of a DCSOP and evaluate potential benefits such as reduced line loading
(C.4) Comparison between DCSOP and simple NOP	Identify differences between DCSOP functionality against a simple DC line equivalent

3.2. DCSOP Stress Test

In this test, the reliability of the DCSOP controller was investigated. Thus, a repeated and a very aggressive step change in the power flow direction was applied to the DCSOP configuration shown in Figure 10, as shown in Figure 11. The results in Figure 12 show that the controller succeeded in keeping the voltage difference between the DCSOP terminals at a constant value (50 V) in spite of the change in power flow direction.
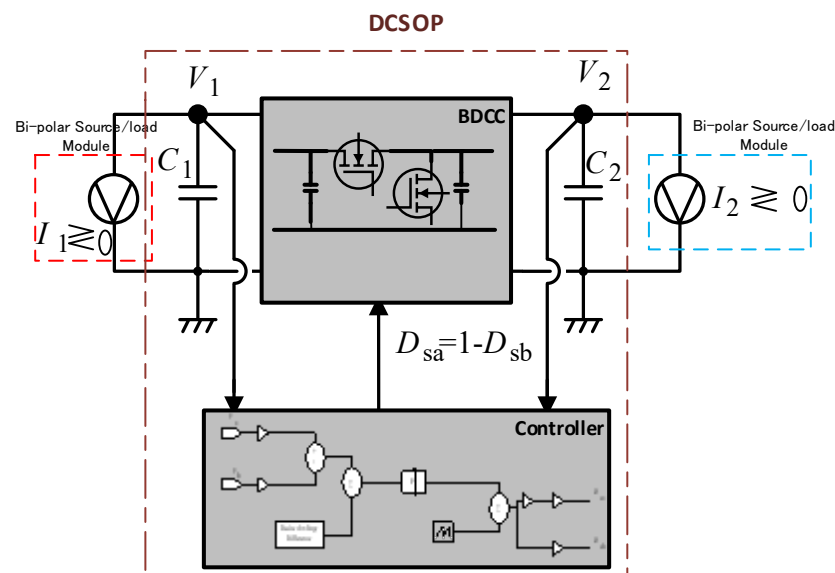

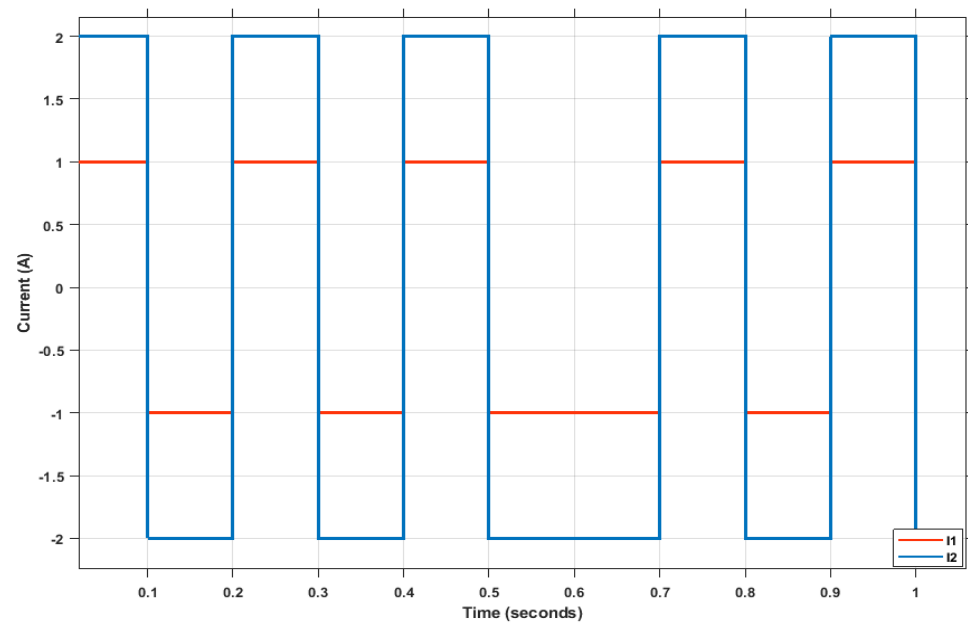**Figure 10.** Configuration for the DCSOP stress test.

Figure 11. Change of the current and power flow direction as a result of a repeated and very aggressive step change in power flow direction.
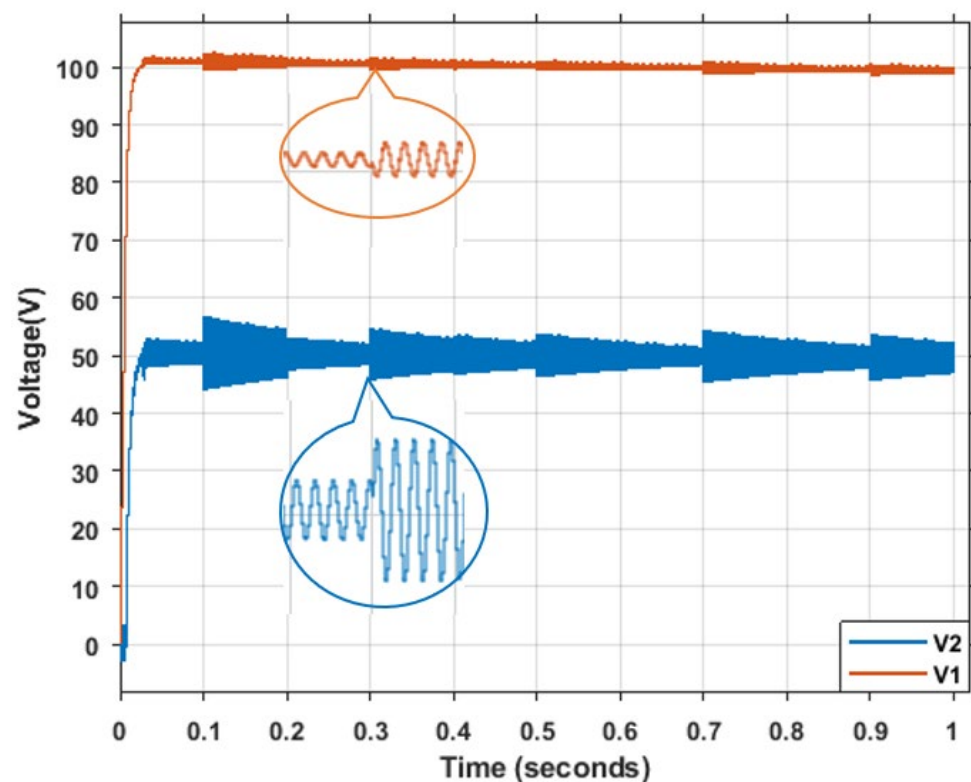

Figure 12. DCSOP terminal voltages as a result of a repeated and very aggressive step change in power flow direction.

3.3. Control of Current Flow Direction

The purpose of the DCSOP controller is to keep the voltage difference between the DCSOP terminals constant at a certain value. Therefore, the voltage at one terminal of the DCSOP will be higher than the other terminal by a particular value. In turn, the current will flow from the terminal with the higher voltage to the other terminal. The current flow direction can thus be controlled. In order to test this functionality, a circuit configuration,

as shown in Figure 13, was implemented and the DCSOP connected between Buses 2 and 5. Once the DCSOP caused the voltage at Bus 5 to be higher than that of Bus 2, the current flowed in the direction shown by the red arrow (from Bus 5 to Bus 2). When the DCSOP controlled the voltage at Bus 2 to be higher than that at Bus 5, the current flowed in the opposite direction. The results in Figure 14 confirm this advantage of including the DCSOP in a DC distribution system.
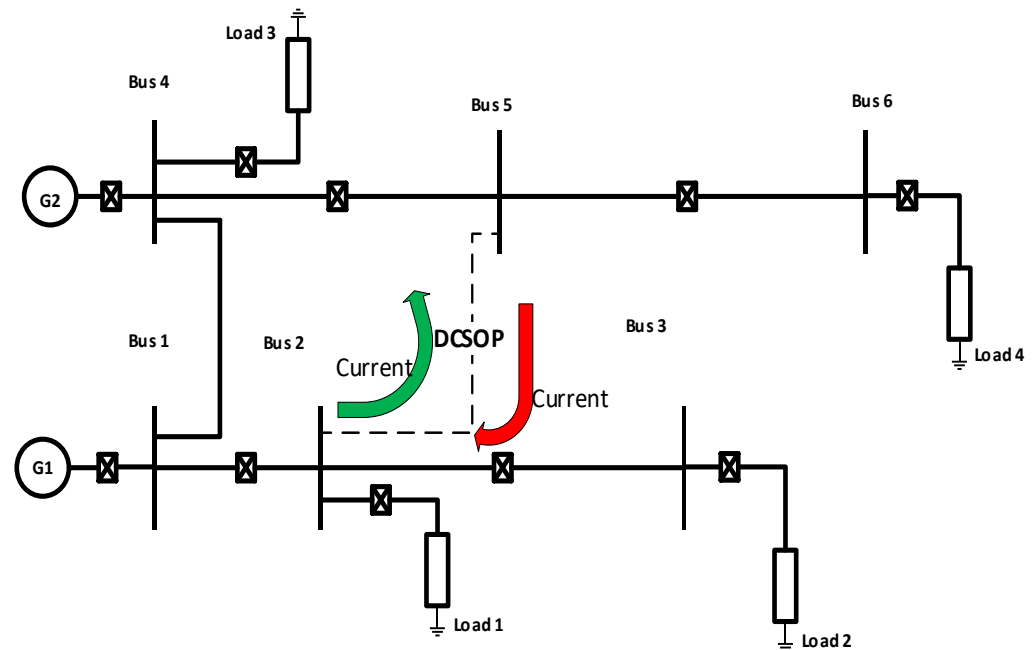

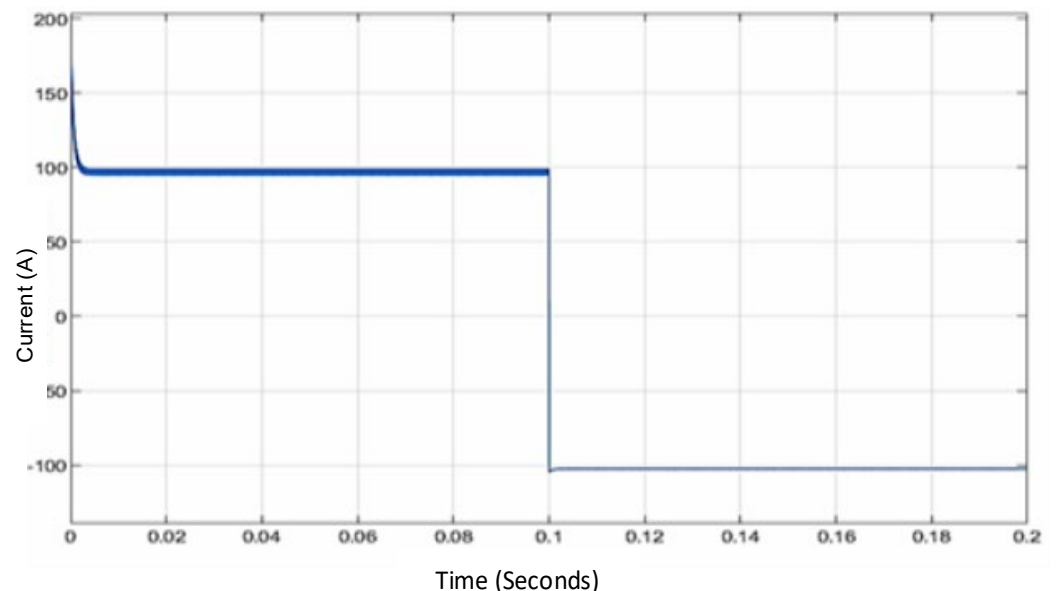**Figure 13.** System diagram for testing the control of the current flow direction.

Figure 14. Current across the DCSOP, showing control of the current flow direction.

3.4. Replacing NOP with DCSOP in a DC Microgrid

The performance of the DCSOP was investigated through integrating it into a DC microgrid. This DC microgrid model, shown in Figure 15, was constructed based on the CERTS AC microgrid described in [56], with the key difference that it was converted to DC. It consists of four feeders, ten buses, seven loads, five generators and two NOPs.

The DCSOP was tested by connecting it to NOP1. Table A1 includes the data of this DC microgrid. The results, in Figures 16 and 17, as well as Tables 2 and 3, show the currents through the feeders and from the generators both before and after connecting the DCSOP. It can be seen that these currents were severely altered by connecting the DCSOP, and this means that the DCSOP can have a strong effect when employed in the reconfiguration of DC distribution systems. In particular, it can be observed that the current across Buses 2 and 6 was dramatically reduced, avoiding potential overloading in that line. Likewise, the output of generators 3 and 4 was distributed more equally.
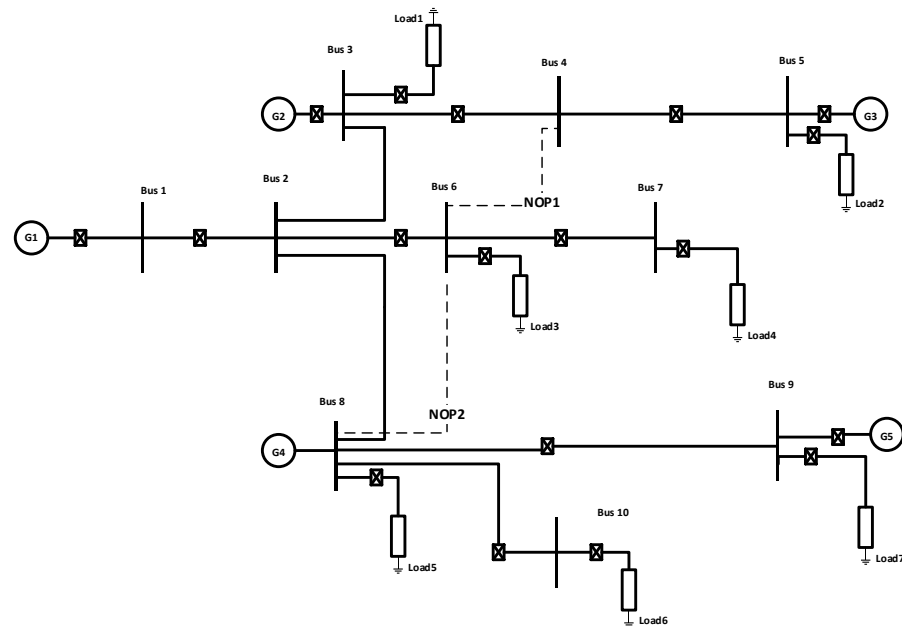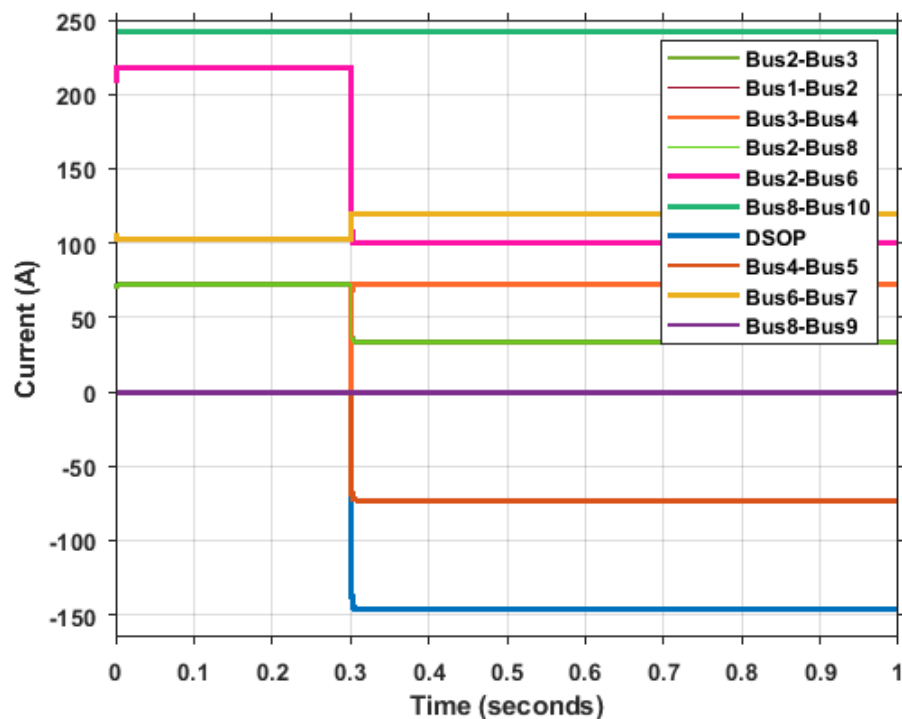

Figure 15. DC version of the CERTS microgrid.

Figure 16. Currents through the DC microgrid feeders before/after connecting the DCSOP.
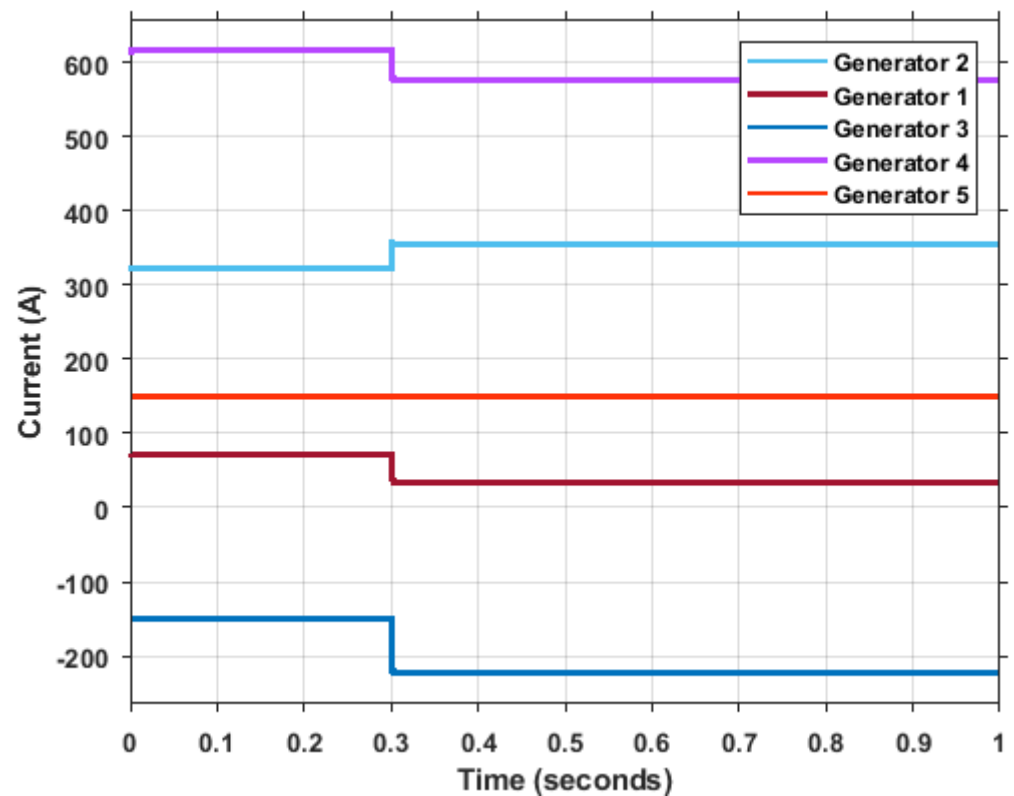
Figure 17. Currents from the DC microgrid generators before/after connecting the DCSOP.

Table 2. Currents through the DC microgrid feeders before/after connecting the DCSOP.

Branches	Currents before Connecting the DCSOP, A	Currents after Connecting the DCSOP, A
Bus 1–Bus 2	72.5	33.3
Bus 2–Bus 3	72.5	33.3
Bus 3–Bus 4	0	72.8
Bus 4–Bus 5	0	−72.8
Bus 2–Bus 6	217.5	100
Bus 6–Bus 7	102.6	119.4
Bus 2–Bus 8	72.5	33.3
Bus 8–Bus 9	0	0
Bus 8–Bus 10	242.3	242.3
DCSOP	0	−145.6

Table 3. Currents from the DC microgrid generators before/after connecting the DCSOP.

Generators	Currents before Connecting the DCSOP, A	Currents after Connecting the DCSOP, A
Generator 1	72.5	33.3
Generator 2	322.5	356.7
Generator 3	−149.8	−222.6
Generator 4	615.5	576.4
Generator 5	149.8	149.8

3.5. Replacing NOP with a Normal Conductor in a DC Microgrid

In order to compare the performance of the DCSOP with that of a normal conductor, the DC microgrid model was modified by closing NOP1 with a normal conductor instead of a DCSOP. The results in Figures 18 and 19 show the similarity of the performance for the

DCSOP and the normal conductor, except for a slight difference in some branch currents. Tables 4 and 5 show a comparison between the performance of the DCSOP and the normal conductor in terms of the change of branch and generator currents before and after the connection. Based on this comparison, it can be concluded that the DCSOP can behave like a normal conductor in connecting the NOPs. However, it has additional merits, such as controlling the current direction and connecting two nodes with different voltage levels.
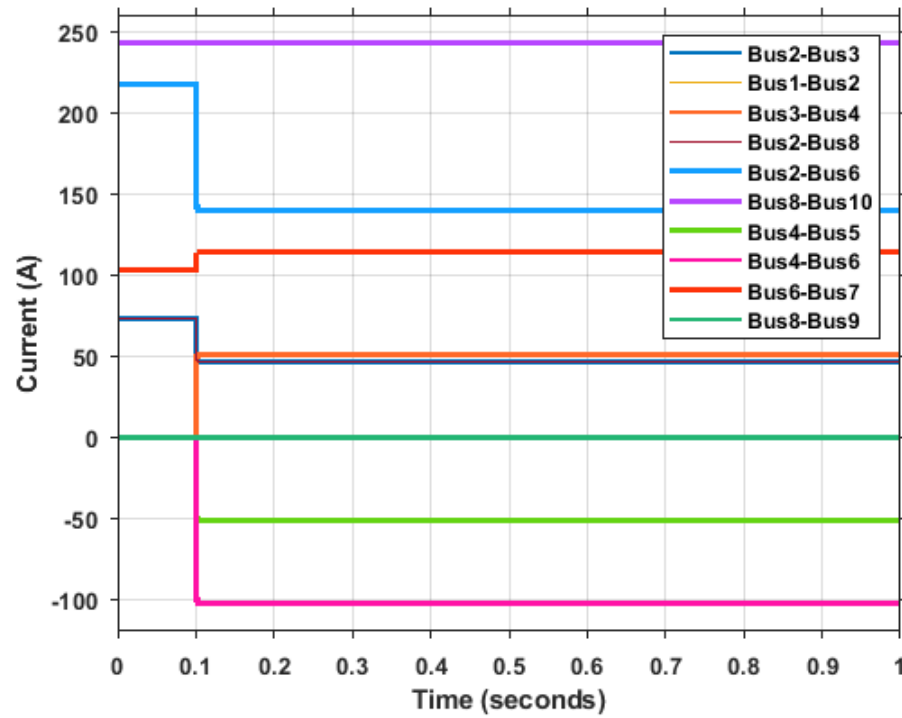

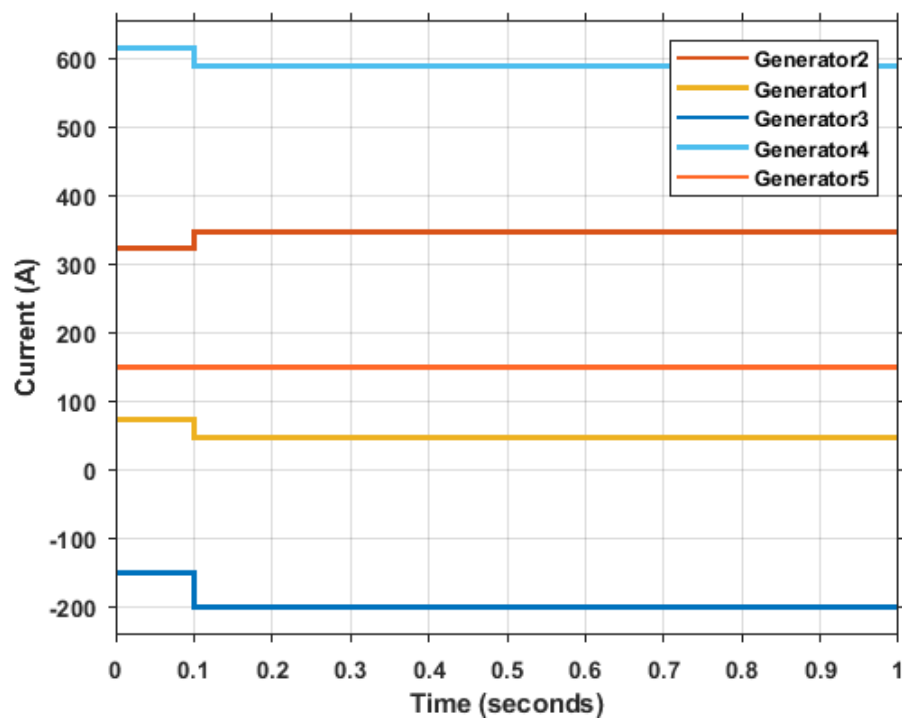**Figure 18.** Currents through the DC microgrid feeders before/after connecting a normal conductor.

Figure 19. Currents from the DC microgrid generators before/after connecting a normal conductor.

Table 4. Comparison between the performance of the DCSOP and the normal conductor in terms of the change of branch currents.

Branches	Currents with NOP, A	Currents with a Normal Conductor Closing the NOP, A
Bus 1–Bus 2	72.5	37.9
Bus 2–Bus 3	72.5	37.9
Bus 3–Bus 4	0	67.6
Bus 4–Bus 5	0	−67.6
Bus 4–Bus 6	0	−135.2
Bus 2–Bus 6	217.5	113.8
Bus 6–Bus 7	102.6	117.4
Bus 2–Bus 8	72.5	37.9
Bus 8–Bus 9	0	0
Bus 8–Bus 10	242.3	242.3

Table 5. Comparison between the performance of the DCSOP and the normal conductor in terms of the change of generator currents.

Generators	Currents with NOP, A	Currents with a Normal Conductor Closing the NOP, A
Generator 1	72.5	38
Generator 2	322.5	355.5
Generator 3	−149.8	−217.4
Generator 4	615.5	581
Generator 5	149.8	149.8

3.6. Impact of DCSOP on Reliability of Reconfigurable DC Microgrids—Case Studies

Four reliability study cases were investigated, and these are described in this section. The network used in these study cases is the microgrid defined by CERTS, as seen in [56]. The microgrid model in [56] is an AC microgrid, whereas in this study the model was converted to a DC microgrid, considering the same or equivalent component ratings. The component failure rates were considered to be uniform, as they are very hard to estimate due to the lack of data on DC components. In any case, they are of minor importance, since the key assessment in this study relates to the network structure of the microgrid rather than the individual components.

The microgrid was reconfigured in three different ways, by linking two pairs of buses in all combinations. The link was performed with a DCSOP, which the authors will be describing in a different publication. The essence of this DCSOP is that it acts as a controllable power electronics switch that can be operated remotely, and that can link two DC buses in different parts of the network. Figure 20 shows the network, including the locations that were considered for the installation of the DCSOPs. The four cases and their results are described in the following subsections.
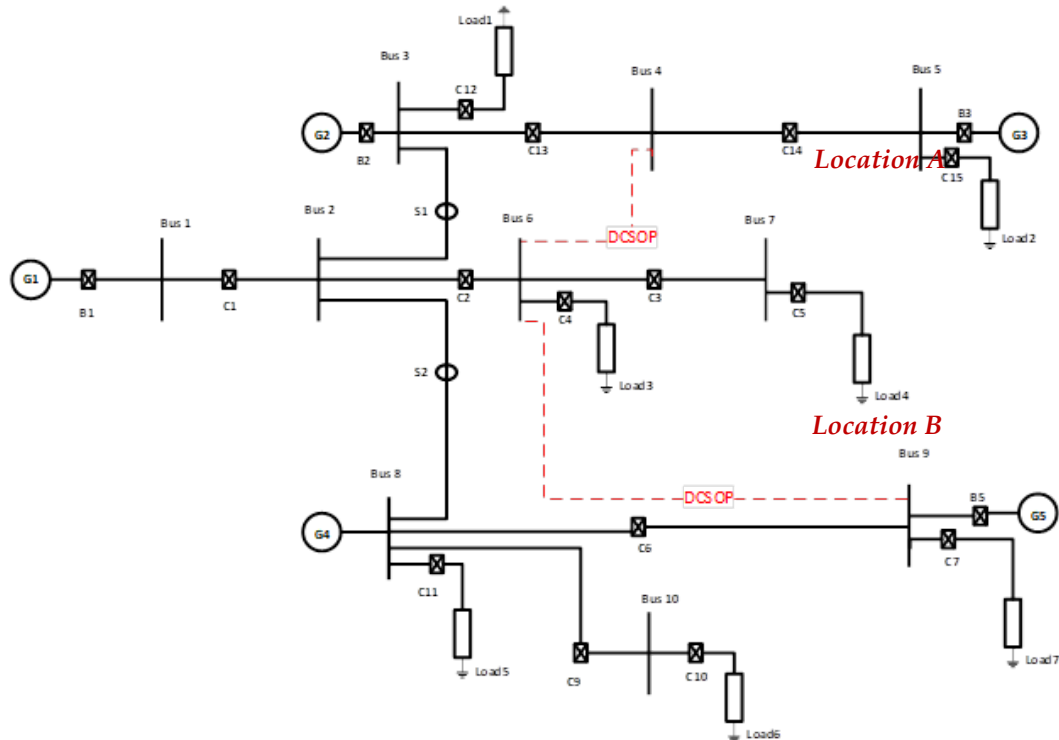
Figure 20. DC microgrid with DCSOP in locations A and B.

3.6.1. Case R.1: Base Case, No DCSOP

In this case, the reliability analysis was conducted for the original DC system without considering any DCSOPs in either Location A or B.

The two reliability indices were calculated as follows:

- CAIDI: 1.269,
- SAIDI: 1.0497.

3.6.2. Case R.2: One DCSOP, Location A

In this case, the reliability analysis was conducted for the original DC system with the addition of one DSCOP between Bus 4 and Bus 6 (Location A in Figure 20). It can be observed that both indices dropped, particularly CAIDI.

The two reliability indices were calculated as follows:

- CAIDI: 0.961,
- SAIDI: 0.964.

3.6.3. Case R.3: One DCSOP, Location B

In this case, the reliability analysis was conducted for the original DC system with the addition of one DSCOP between Bus 9 and Bus 6 (Location B in Figure 20). This type of reconfiguration seems to be more effective, as the SAIDI index dropped further. The CAIDI index is almost the same as Case R.2, although marginally higher.

The two reliability indices were calculated as follows:

- CAIDI: 0.964,
- SAIDI: 0.7461.

3.6.4. Case R.4: Two DCSOPs, Locations A and B

In this case, the reliability analysis was conducted for the original DC system with the addition of two DSCOPs. This reconfiguration case yielded the most significant improvements, since both indices dropped significantly. The CAIDI index in particular is almost half that of the original Case R.1.

The two reliability indices were calculated as follows:

- CAIDI: 0.658,
- SAIDI: 0.656.

3.6.5. Summary and Comparison of Reliability Cases

A comparison of all four cases is presented in Table 6. The percentage improvement against the base case (Case R.1) is also provided. It can be seen that Cases R.2–R.4 present a significant reduction in both indices.

Table 6. Comparison of all reliability cases. Case R.1 is the base case.

	CAIDI	% Improvement	SAIDI	% Improvement
Case R.1	1.269	-	1.0497	-
Case R.2	0.961	24.3%	0.964	8.1%
Case R.3	0.964	24.0%	0.7461	28.9%
Case R.4	0.658	48.1%	0.656	37.5%

3.7. Testing of Agent-Based Control of DCSOP for DC Network Reconfiguration

The sequence diagram of the interaction between the two agents can be seen in Figure 21a. The interactions demonstrate that when the load agent decides that the load is low, then it signals to the DCSOP agent to transition to the OFF state. Hence, in the next iteration, the DCSOP agent transitions to the OFF state. Conversely, when the load agent decides that the load is high, it signals to the DCSOP agent to transition to the ON state. Hence, in the next iteration, the DCSOP agent transitions to the ON state.
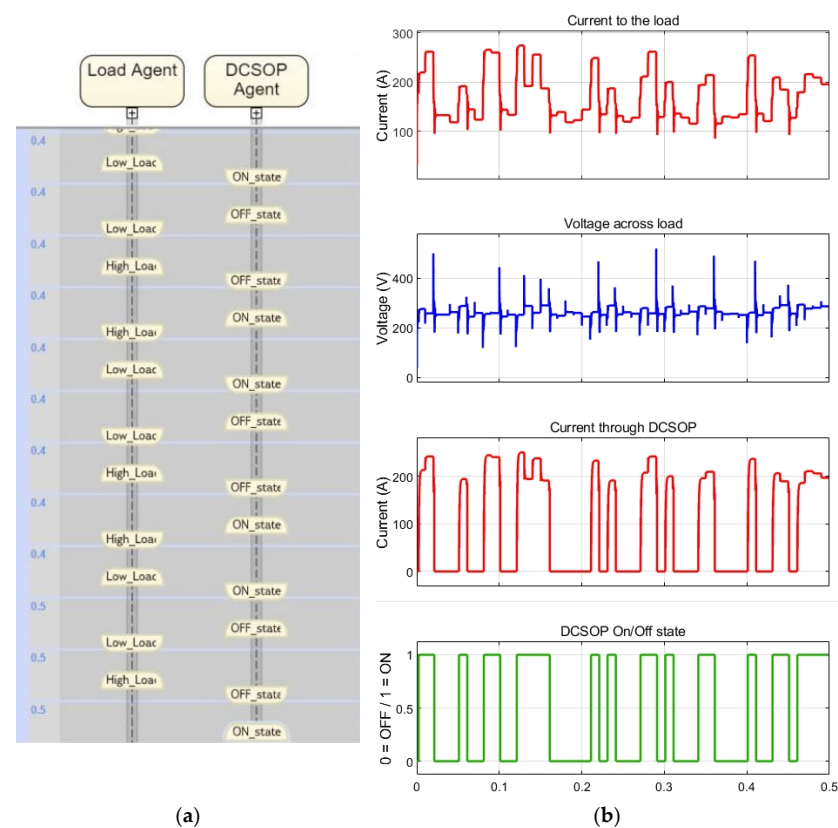

(a)　　　　　　　　　　　　　　　　　　　　(b)

Figure 21. (**a**) Agent states sequence and (**b**) results from DC microgrid simulation over a period of 0.5 s, as shown in the horizontal axis.

The measurements from the DC microgrid can be seen in Figure 21b. It can be seen that the DCSOP transitions between the ON and OFF state several times throughout the

simulation. The current that passes through the DCSOP is non-zero when it is in the ON state and zero when it is in the OFF state. Its value when it is in the ON state depends on the power flows in the circuit, hence the precise value of the load.

The switching of the DCSOP caused significant transient effects, but the transient performance of the system was not considered in this particular study. One important observation is that the steady-state voltage across the load remains relatively stable, despite the fluctuations of the load. This can be explained by the fact that when the load is high, the DCSOP is on; hence, the power is being routed towards that load from more than one source. Voltage transients can also be observed, which are most likely due to the switching operation of the DCSOP and the reactive elements of the circuit.

The above demonstrates that a DCSOP controlled by agent-based systems can be used for voltage regulation in a DC microgrid.

4. Conclusions

This paper presented the novel concept of the DC soft open point as a tool for reconfiguring DC distribution networks. The model of the DCSOP was presented, along with controller schematics and a state space analysis. Four characterisation case studies were simulated to evaluate the operational performance of the DCSOP within a DC microgrid. The results show that the proposed DCSOP concept can be used to effectively reconfigure a DC network. In some cases, the power flow distribution was altered with beneficial reductions in the loading of some lines. With careful coordination, such a reconfiguration can prevent the overloading of DC lines and other equipment, and enable the optimal utilisation of assets. It has also been proven that the DCSOP offers additional functionality and control to the system operator, by:

a.   Being able to control the power flows, and
b.   Being able to connect two buses operating at different voltages.

In addition, the effectiveness of the DC network reconfiguration for improving reliability was evaluated. An established method for reliability evaluation based on segmenting power networks was used. Four reliability case studies were set up. The first one was a DC conversion of the CERTS microgrid testbed, without any reconfiguration. The remaining case studies considered reconfiguring the DC microgrid with a DC soft open point. Two reconfiguration points were considered and the scenarios involved all combinations. The reliability indices, CAIDI and SAIDI, were calculated for all cases. It was found that the most effective way of improving reliability is to reconfigure the network with two DCSOPs. In that case, the reliability indices were almost halved. The reason for this is likely that there are multiple alternative routes for the power to reach the load in the case of a failure in the network.

Finally, an agent-based framework was presented for the control of a DCSOP power electronics device by an intelligent agent. The purpose of this framework was to enable DC microgrid control and reconfiguration. The framework was implemented in MAT-LAB/Simulink and a test case presented, using an AC microgrid converted to DC. One DCSOP device was placed between two buses of the microgrid and an agent was attached to it. The operation of this fundamental agent-based system was demonstrated, and this will be used as the basis for further development of more elaborate agent-based systems. The results show that the DCSOP transitions between ON and OFF states, as instructed by the agent, based on the load levels at a particular bus. The outcome of that is that the steady-state voltage of that particular load does not drop unnecessarily when the load increases. This is due to the fact that by turning the DCSOP device on, alternative routes are provided for the power to reach that load. Future extensions of this work include the study of the effects of power electronics converters and their coordination with the existing protection devices. In addition, multi-objective analysis can be conducted with the other power quality factors, such as harmonic distortions and efficiency.

Appendix A

Table A1. Data of the simulated DC microgrid.

Branches	R/Ω	Loads	Rating/KW	Generators	Rating/V
Bus 1–Bus 2	1.32	Load 1	100	G1	400
Bus 2–Bus 3	1.32	Load 2	60	G2	400
Bus 3–Bus 4	1.32	Load 3	60	G3	400
Bus 4–Bus 5	1.32	Load 4	60	G4	400
Bus 2–Bus 6	1.32	Load 5	30	G5	400
Bus 6–Bus 7	1.32	Load 6	30		
Bus 2–Bus 8	1.32	Load 7	60		
Bus 8–Bus 9	1.32				
Bus 8–Bus 10	1.32				

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