4th Conference on Production Systems and Logistics

Source Management In DC-Microgrids: An Industrial Application

Isabella Bianchini[1], Jonas Knapp[1,2], Simon Riethmüller[3], Thorben Kwiatkowski[3], Xiaotian Yang[4], Alexander Sauer [1,2]

[1] *Institute for Energy Efficiency in Production (EEP), University of Stuttgart, Germany*
[2] *Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany*
[3] *HOMAG GmbH, Schopfloch, Germany*
4 Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Erlangen, Germany

Abstract

Industrial direct current (DC) microgrids offer multiple advantages for production factories. They enable higher energy and resource efficiency not only for the production energy supply but also for integrating renewable energy resources. The basic control method of DC microgrids, namely droop control, fits the industrial application due to its decentralized and robust nature. However, in the case of droop control, the DC bus voltage deviates from the nominal value for slowly fluctuating load situations. For this reason, an additional control level for voltage restoration, called secondary control or source management, is necessary. This paper presents hierarchical control for voltage restoration in industrial DC microgrids. The control shifts the current supplied to the DC bus in case the load increases over or decreases below a defined voltage band for a certain period. In addition, the designed control is tested on a real industrial DC microgrid which includes typical industrial loads of up to 50 kW, such as robots of different sizes and CNC machine tools. The control performance with different parameters of the source management is assessed. The results show that the designed control restores the voltage level without creating instabilities in the microgrid for all tested scenarios.

Keywords

Industrial microgrid; direct current supply; droop control; hierarchical control; voltage deviation;

1. Introduction

Over the past years, the concept of direct current (DC) microgrids for integrating renewable energy sources has been proposed and studied. Renewable generation, such as photovoltaic (PV) and wind, inherently foresees the presence of a DC-DC or AC-DC conversion step for the grid connection. Due to their nature, their integration in DC grids is more efficient than in alternate current (AC) grids [1]. In addition, compared to the AC microgrids, DC microgrids overcome disadvantages such as frequency synchronisation, reactive power control, and skin effect [2]. The interest in DC microgrids and technologies has been growing in many sectors, such as residential, data centres, electricity distribution, and industry [3–5]. In the industrial sector, where the loads are increasingly being supplied by converter technologies, DC technology and microgrids have gained attention [6]. For industrial DC applications, a reduction of conversion losses of up to 3.75 % for loads and 7 % for storage systems have been estimated [7]. In addition, the DC technology enables braking energy recovery from drives and the supply of this energy into the grid instead of being converted into heat through braking resistors [8]. In the case of a Computerized Numerical Control (CNC) machine, the combination of reduced conversion losses and recuperation of braking energy resulted in an overall

DOI: https://doi.org/10.15488/13423
ISSN: 2701-6277

energy efficiency increase of 6.2 % [7]. In the case of industrial robots, Meike et al. estimated a recuperation potential of 15 % during operation. Resource efficiency of industrial companies can be improved by DC microgrids due to the reduced cabling requirements and the elimination of conversion steps [7]. Two phases of the German research project DC-INDUSTRIE proposed the concept of a non-proprietary DC microgrid, which aims at spreading DC microgrids in the industrial sector [9,10].

Droop control is the basic control method for DC microgrids. It is a decentralized control method based on a control loop over the converters' inner voltage and current control loops. The control uses a virtual resistance or conductance to define the target voltage (current droop control) or the target current (voltage droop control) at the device´s connection point to the DC bus [6,11]. However, it has two main limitations, the current sharing among converters and voltage deviation [1,12]. The voltage deviation is an inherent consequence of the droop control. In the case of high load, the converter with voltage droop curve compensates the load with higher current and the voltage is shifted towards lower values. In the case of low loads, the voltage is shifted towards higher voltage values. The DC bus voltage is located outside the nominal voltage band in both cases. In order to compensate for the voltage deviation, multiple approaches have been proposed in literature. These approaches are based on a higher control level, called the secondary control level [12] or source management [13], over the droop curve control. According to communication requirements, source management can be classified as decentralized, distributed and centralized [14].

This paper proposes a source management for nominal voltage restoration for industrial DC microgrids. In addition, the results of an actual application in a small-scale industrial DC microgrid are presented. The paper proves that, despite the simplicity of the approach, the control manages to restore the voltage level. The paper is structured as follows. Section 2 introduces the state of the art of secondary or source management of DC microgrids. Section 3 describes DC microgrid concept and defines the industrial system for the tests. Section 3 introduces the hierarchical control approach based on droop curves-based primary control and source management for voltage restoration. Then, section 4 applies the control approach exemplarily to the industrial system before presenting and discussing the results. Finally, section 5 offers a summary and outlook.

2. State of the art

In [15], the secondary level of the DC microgrid control proposed by Nutkani et al. aims at current sharing and voltage restoration and operates over the droop control level. It considers economic values, such as generation costs and grid tariff. The centralized second control level shifts the voltage to restore the nominal voltage level. The control does not require a high bandwidth communication, and it is tested in simulations. Zhao et al. in [16] propose a piecewise droop control strategy for improved voltage regulation. Multiple current droop curves for each converter are defined that can be changed in a decentralized manner according to the load situation. The effective switch between droop curves is tested in a laboratory-scale 30 V DC microgrid with two converters and resistive loads. In [1], Lu et al. propose a distributed hierarchical control system for voltage restoration and current sharing. A low-bandwidth communication scheme for exchanging local output current and voltage measurement between the secondary controllers is defined. The current and voltage measurement is used for the definition of voltage and current shift values, which are then combined with the results of the droop control. The control is tested in MATLAB/Simulink simulations. Nasirian et al. in [17] define a similar distributed secondary control system based on two modules, a voltage controller, and a current controller. Here, the voltage controller is based on a cooperative voltage observer for the global voltage estimation. The current control compares local currents and neighbouring currents to adjust the virtual droop resistance. The control system is tested on a DC microgrid prototype with a rated voltage of 48 V. A real-time control for voltage restoration and current sharing in DC microgrids is proposed by Olives-Camps et al. in [18]. The control can solve optimization problems without requiring a precise model. Control performances are assessed in simulations, testing both centralized and distributed control implementation. It

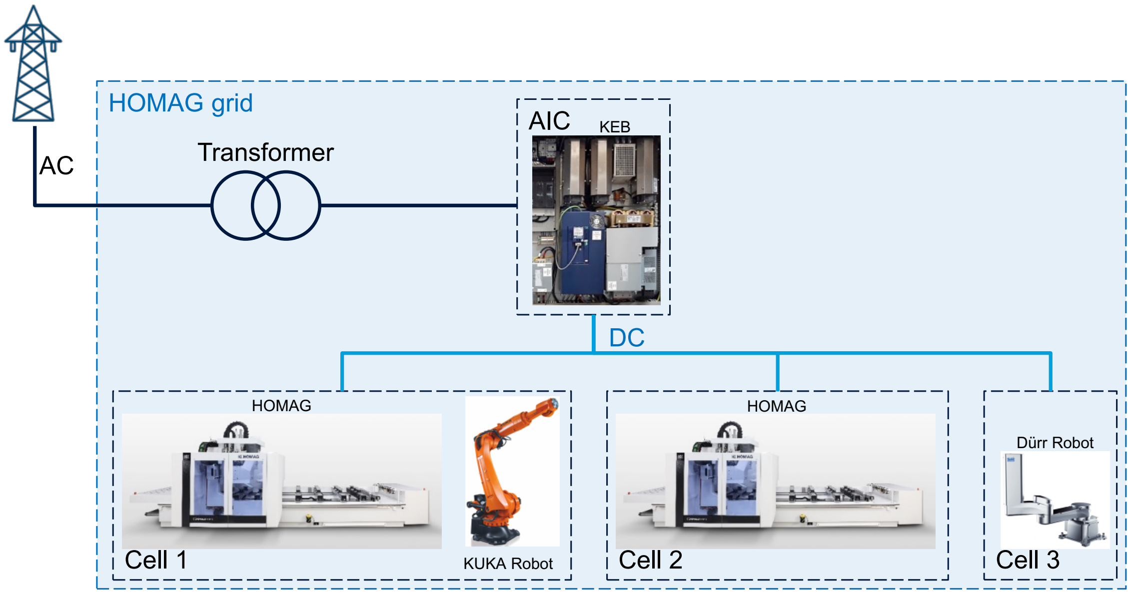

Figure 1: Structural diagram of the electrical DC microgrid at HOMAG plant. An active infeed converter (AIC) is the interconnection point between the AC grid and DC microgrid and supplies the consumers in three cells.

is shown that the control is robust, the distributed implementation has good dynamic performances, and reduces communication requirements.

The proposed control approaches can restore the voltage level and improve the DC microgrid performance. However, some of the proposed control strategies are highly complex and require communication between converters. The design of the hierarchical control for industrial microgrids should guarantee simplicity and reliability [13]. Moreover, in industry the attractiveness of effective but simple and reliable control systems increases when the approaches have been successfully tested in an actual industrial system. However, here mostly simulation and laboratory-scale microgrids are tested.

3. Description of the industrial DC microgrid

Figure 1 shows the typical structure of a DC grid, here using the HOMAG DC microgrid as an example. All devices are connected to a DC bus consisting of a power rail distributing power within the devices. An active infeed converter (AIC) feeds the bus system. The AIC is the interconnection point between the AC and the DC grid and transforms the voltage to the appropriate level [10]. In addition, there was an energy storage system, a lithium ion battery with a capacity of 200 Ah (two battery cells with 100 Ah and 50 V each). However, it was not used in the test and thus is not shown in Figure 1. The consumers of the DC grid comprise three cells. The first cell includes a HOMAG woodworking machine and a robot. The robot in cell 1 loads the machine with workpieces. The second cell uses another woodworking machine similar to the one in the first cell, but without robot. The third cell is the smallest in terms of power, as only a small robot is integrated.

For the following sections, it is necessary to define active devices and to distinguish them from passive ones. Each active device receives a predefined droop curve and adjusts its supply and/or consumption according to the DC bus status. Therefore, the active device is actively involved in the control of the DC microgrid. For the DC grid used in this paper, the AIC is the only active device and the three consumer cells are passive devices.

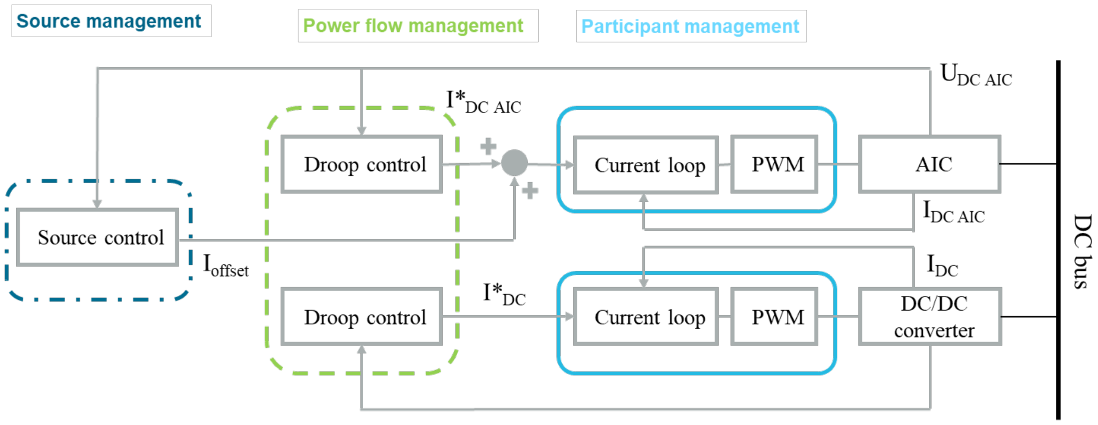

Figure 2: Schematic representation of the hierarchical control for the industrial DC microgrid used in this paper. The control includes power flow management (primary droop control) and source management (secondary control). Participant management is out of the scope of the paper.

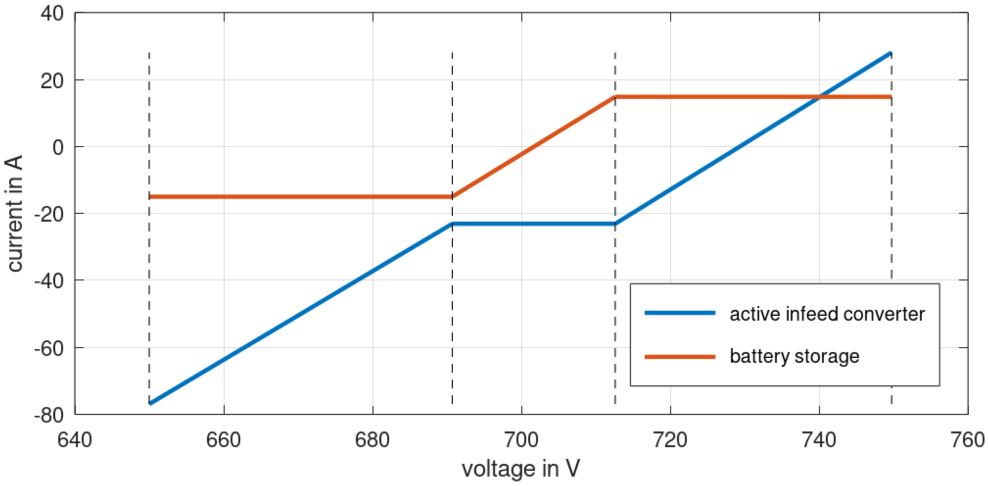

Figure 3: Example of droop curves including an AIC and battery storage system.

4. Control design

The DC microgrid control presented in this paper is a hierarchical control. The lower level is based on the on droop curves and the higher level is managed by a secondary control, the source management (Figure 2). The droop control is designed for all the active participants of the microgrids [13]. The source management operates in a centralized way, delivering a current offset that is added to the current defined by the active participants' droop control. Only the active devices included in the source management receive the current offset. The following paragraph describes both control levels. The lowest control level, also referred to as participant management, is out of the scope of this paper.

4.1 Droop curve control design

To control voltage and balance power within the DC grid, every active device measures its voltage and adapts its power infeed proportionally to the voltage deviation. The droop curve-based approach does not depend on digital communication and has the smallest possible response time, only limited by converter dynamics. **Error! Reference source not found.** shows an example of droop curves of the AIC and the battery storage. Devices supply the DC microgrid if the current is negative, while they absorb power from the grid if the current is positive. The vertical dotted lines divide three areas in which only one device actively adjusts its power infeed to the voltage variations. In this case, the respective droop curve has a positive power

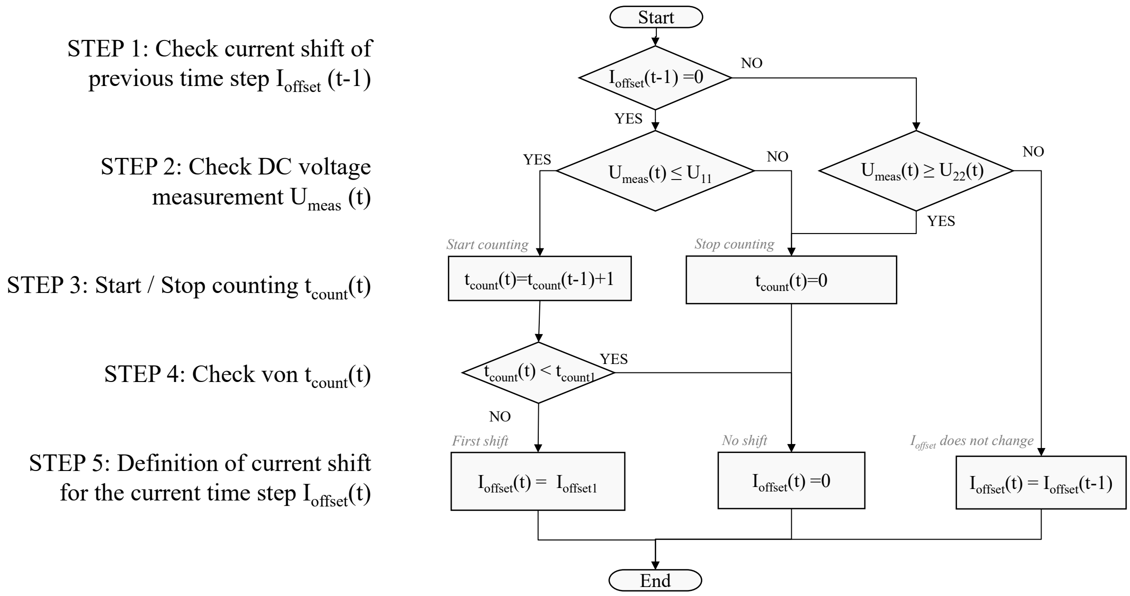

Figure 4: Flowchart of the source management implemented on the PLC of the active infeed converter (AIC) for voltage restoration. Considered case: high load.

gradient. At the same time, the other device supplies a constant power, which does not depend on the voltage, and its droop curve gradient is equal to zero. More details about droop curves and the relevant parameters can be found in literature [6,10].

Depending on the design of the droop curve, certain functions, such as peak shaving, are implemented. The operating point in normal mode is between the inner two dotted lines [690 V; 716 V]. In this area, the AIC constantly feeds around 23 A into the DC grid while the battery storage compensates for power deviations and thus operates peak shaving. Other functions that can be implemented are: charge/ discharge storage, feed into DC grid, feed back into AC grid, or uninterruptible power supply.

As previously described, the AIC is the only active device in the HOMAG microgrid and, thus, the only device with a droop curve. Its droop curve corresponds to the one in Figure 3.

4.2 Source management design

If the loads are higher than the nominal ones, the voltage level in a DC microgrid is reduced. If this higher load stagnates for a longer time, an undesirable operating point closer to the stability limit will be used. The aim of the source management designed in this paper is to restore the voltage level at the nominal value. The control is centralized and operated by the AIC's programmable logic controller (PLC). Figure 4 shows the flowchart of the source control as implemented in the AIC's PLC.

In order to restore the nominal voltage, the control activates a current shift that is added to the droop curve target current and increases the current delivered by the AIC. The negative shift (more current supplied to the microgrid) is activated if the measured DC bus voltage is lower than a certain voltage threshold U_{11} for more than a predefined time limit t_{count}. This way, the source management is activated only when the loads are higher than nominal power for longer periods. To avoid frequent activation and deactivation, the I_{offset} is set back to zero in case the voltage overcomes a second threshold U_{12} higher than U_{11}.

The same can be defined for low loads and high voltage levels. In this case, the shift will be positive (less current supplied to the microgrid) and the voltage thresholds will be higher than the nominal voltage, with $U_{22} < U_{21}$. This part of the control is not tested and is out of the scope of this paper.

5. Results

This paragraph describes the results of applying the proposed control design (section 4) in the industrial system described in section 2. To test the designed control, different scenarios were defined (see Table 1). In the first scenario, only the droop curve-based control is considered, and the source management is deactivated. The scenarios SM1, SM2, and SM3 differ due to the value of U_{12}. Scenario SM4 is an extreme scenario differing from SM1 because of doubled current offset and longer counter time.

Figure 6 shows the results of the first two scenarios, where voltage and current profiles are compared. The effect of the control is apparent. When the voltage at the AIC's DC side remains longer than 0.5 seconds under 695 V, then the secondary control is activated, and the I_{offset} is added on the droop curve, causing the shift in the current (examples: 38.19 s, 40.77 s, and 41.54 s). On the other hand, the secondary control is deactivated, and the I_{offset} is set back to zero when the voltage overcomes the second voltage limit U_{12} of 700 V (examples: 40.05 s, 40.98 s, and 41.82 s). When activated, the secondary control causes a small voltage overshoot during the settling time. In this scenario, the voltage step is not sufficient to reach an inflection point of the droop curve, as it happens after the first shift in the figure (38.19 s): even if the voltage exceeds

Table 1: Test scenarios description and parameter definition.

Scenario	Description	U_{11} [V]	U_{12} [V]	I_{offset} [A]	t_{count} [s]
Droop	Droop-curve control only	0	0	0	0
SM1	Droop-curve & source management 1	695	700	-5	0.5
SM2	Droop-curve & source management 2	695	702	-5	0.5
SM3	Droop-curve & source management 3	695	705	-5	0.5
SM4	Droop-curve & source management 4	695	700	-10	0.8

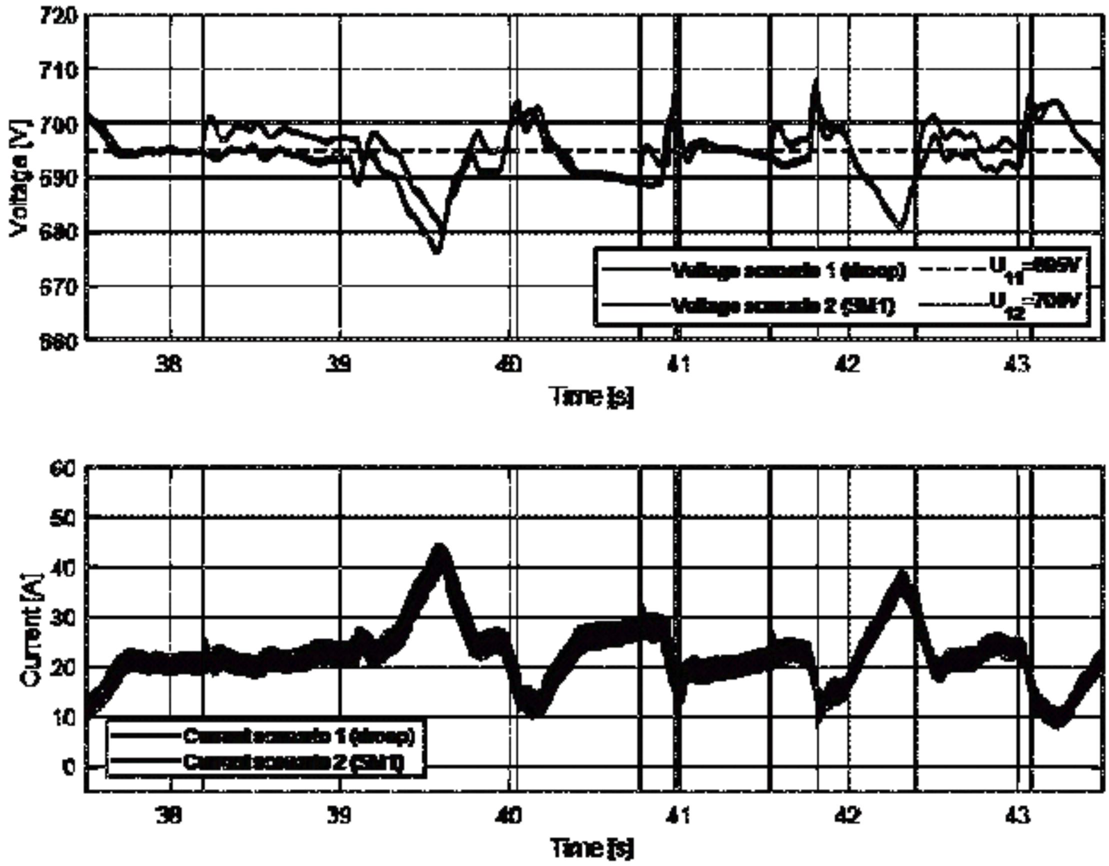

Figure 5: Results from scenario 1 (droop) and 2 (SM1), voltage measurements top, current measurement bottom.

the limit voltage of 700 V, the control is not deactivated until 40.77 s. Since the control operates on the current, the shift is almost instantaneous (current step). However, after circa 100 ms, the dynamics end and the supplied current of scenario SM1 follows the current of scenario "droop". In both scenarios, the system remains stable. Similar voltage and current profiles are measured in scenarios SM2 and SM3 but with later deactivation times of the control. Different are the profiles obtained in scenario SM4. Figure 7 presents the results of the last scenario. The activation is followed by a deactivation after less than 100 ms. This is due to the high current step caused by the control and the fast voltage increase over 700 V, which deactivates the shift. This happens in all the cases showed in Figure 7 except for the activation at 39.48 s. In this case, the load has a peak and shift in current is not enough to overcome the threshold of 700 V. Also in this scenario, the system remains stable.

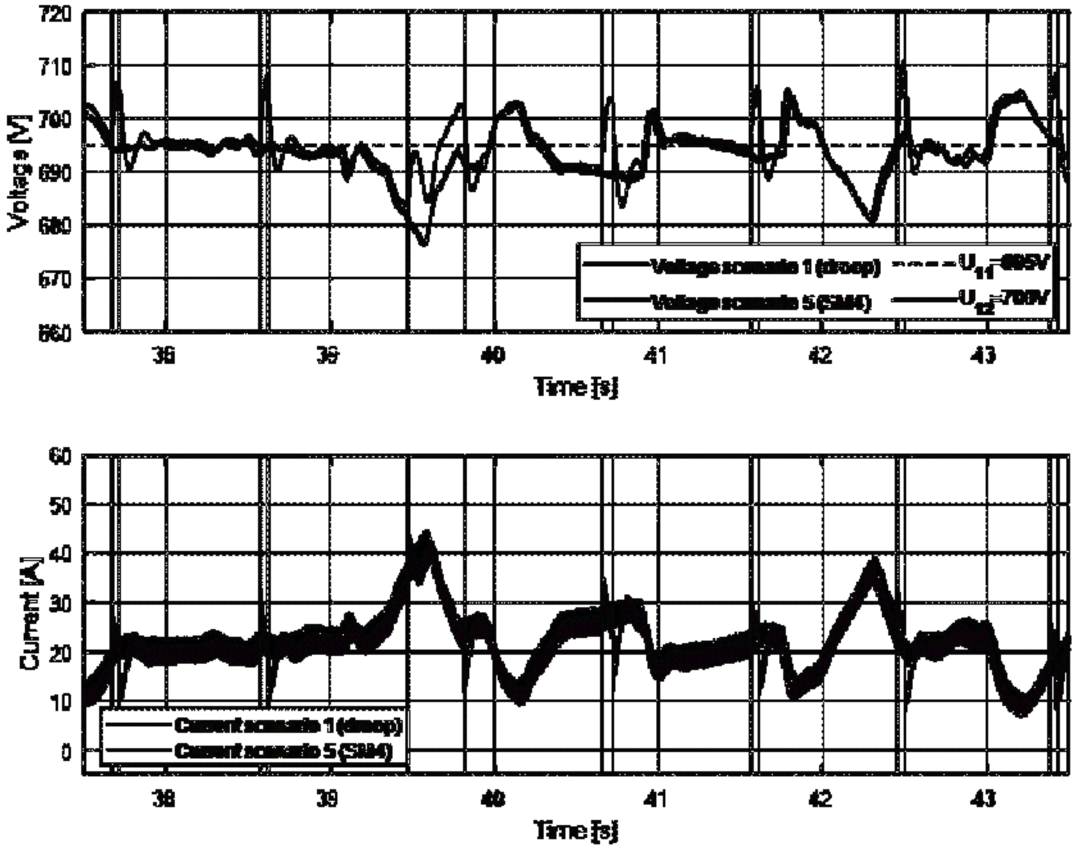

Figure 6: Results from scenario 1 (droop) and 5 (SM4), voltage measurements top and current measurement bottom.

Table 2: Performance parameters for the results assessment. *Active control time for scenario SM2 could not be measured during the test.

Scenario	Active control time	Min. voltage [V]	Max. voltage [V]	Mean voltage [V]	Median voltage [V]	Standard deviation voltage [V]
Droop	0%	667.0	711.1	693.3	694.1	6.0
SM1	45%	667.8	712.3	695.3	696.1	5.5
SM2	-*	667.6	713.8	695.6	696.3	5.6
SM3	83%	670.8	715.6	697.3	698.1	5.5
SM4	9%	668.9	717.9	694.5	694.9	5.9

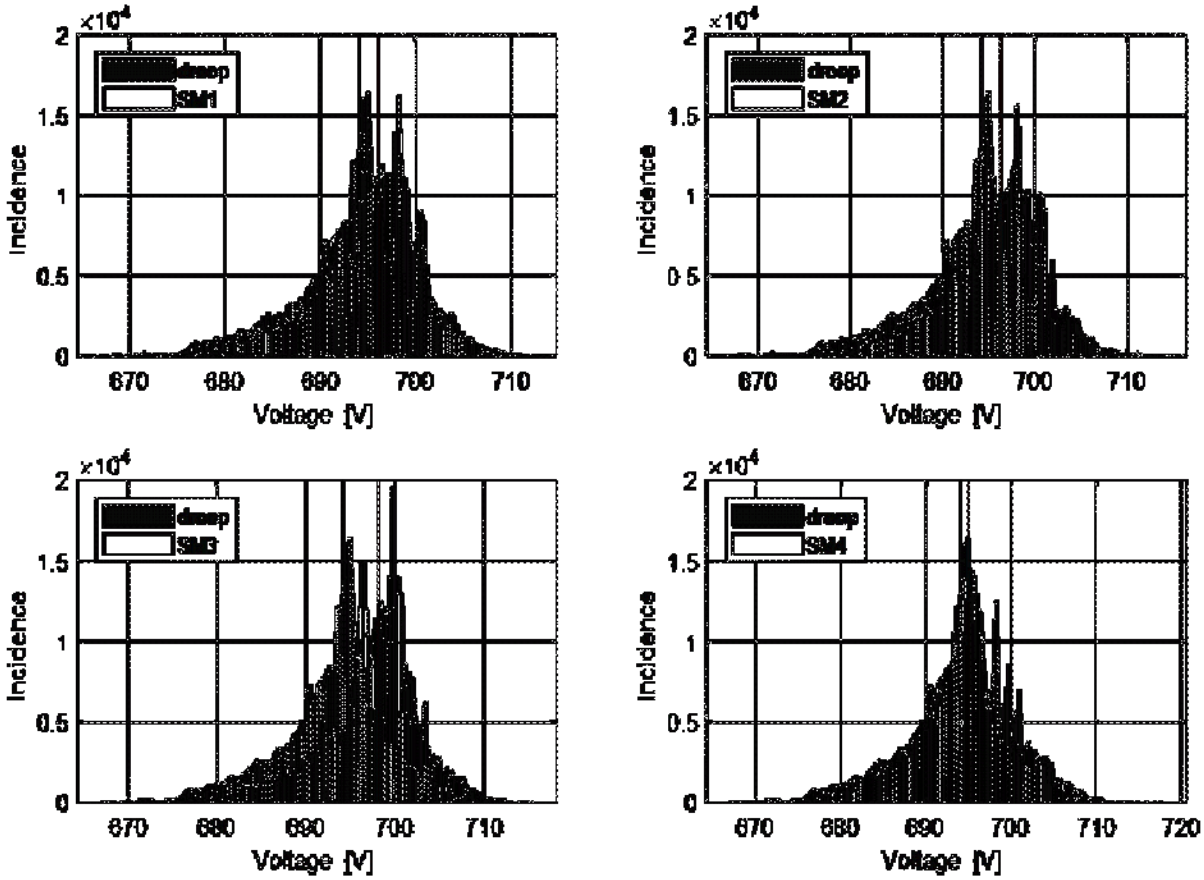

Figure 7: Histograms of measured voltage incidence. Each scenario with source management is compared to the droop curve only scenario.

To systematically assess the results, performance parameters were defined (Table 2). Active control time is when the source management is active, and the current shift is equal to I_{offset}. Increasing U_{12} has the effect of a longer maintained droop curve shift. Differently, in SM4, the active time is only 9 % of the test time. This is due to the voltage overshoot after activation and the almost direct deactivation of the control. Even if the parameter could not be calculated for scenario SM2 due to measurement problems, it is possible to assume that the active control time increases with the voltage limit U_{12}.

The control in all scenarios SM1-4 increases both the minimum and maximum DC voltage. The minimum voltage variation compared to scenario droop is not remarkable in scenarios SM1, SM2, and SM4 and increases up to 3.8 V for scenario SM3. The maximum voltage variation compared to scenario droop increases consistently with the increased voltage limit *U12*. The same effect has the high current shift in scenario SM4, in which the voltage reaches a peak of 717.9 V.

Mean and median voltages consistently increase with the voltage limit *U12*, from 2.0 V to 4.0 V difference with scenario droop. However, in scenario SM4, the mean and median variation from scenario droop is limited to 1.2 V and 0.8 V. This is due to the limited active time of the control: even if minimum and maximum voltages are higher, the control does not affect the average voltage.

Regarding the voltage standard deviation, a decrease can be observed. In particular, for scenario SM1-3, the voltage values are more concentrated around the mean values. In Figure 8, the incidence of voltage levels is presented in histograms. The median is shifted right, thanks to the source management (SM1-3). In case of SM4, the difference is barely visible due to the limited control active time.

6. Conclusion

This paper presents the concept of a hierarchical DC microgrid control for voltage restoration. Source management operates over the droop curve control level to restore the voltage at the nominal level through a current shift. The control concept is implemented and tested on an actual application, a real industrial DC microgrid, including different robots and woodworking machines for a load of up to 50 kW. The results show that this simple control concept can shift the voltage to higher values in all test scenarios. In addition, no instability occurs. Therefore, this control concept is promising for the installation in industrial DC microgrids. Further research should include the definition of a method for computing the source management parameters based on the load profile and the formal investigation of the control stability. Future applications should test the low load case, i.e., the voltage shift towards lower voltage levels in case of low load, and test other DC microgrids with different devices and load.

Acknowledgements

The authors gratefully acknowledge financial support by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) via grant numbers 03EI6002L, 03EI6002N and 03EI6002D (project: “DC-INDUSTRIE 2 - Gleichstrom für die Fabrik der Zukunft“).

References

[1] Lu, X., Guerrero, J.M., Sun, K., Vasquez, J.C., 2014. An Improved Droop Control Method for DC Microgrids Based on Low Bandwidth Communication With DC Bus Voltage Restoration and Enhanced Current Sharing Accuracy. IEEE Trans. Power Electron. 29 (4), 1800–1812.

[2] Liu, Q., Tao, Y., Liu, X., Deng, Y., He, X., 2014. Voltage unbalance and harmonics compensation for islanded microgrid inverters. IET Power Electronics 7 (5), 1055–1063.

[3] Chen, S.-M., Liang, T.-J., Hu, K.-R., 2013. Design, Analysis, and Implementation of Solar Power Optimizer for DC Distribution System. IEEE Trans. Power Electron. 28 (4), 1764–1772.

[4] Dong, D., Cvetkovic, I., Boroyevich, D., Zhang, W., Wang, R., Mattavelli, P., 2013. Grid-Interface Bidirectional Converter for Residential DC Distribution Systems—Part One: High-Density Two-Stage Topology. IEEE Trans. Power Electron. 28 (4), 1655–1666.

[5] Schaab, D.A., Weckmann, S., Kuhlmann, T., Sauer, A., 2018. Simulative Analysis of a Flexible, Robust and Sustainable Energy Supply through Industrial Smart-DC-Grid with Distributed Grid Management. Procedia CIRP 69, 366–370.

[6] Schaab, D.A., Sauer, A. DC-Microgrids will change Electric Power Supply in German Industry, in: , World Sustainable Energy Days 2020, 4 - 6 March 2020, Wels / Austria.

[7] Kuhlmann, T., Bianchini, I., Sauer, A., 2020. Resource and energy efficiency assessment of an industrial DC Smart Grid. Procedia CIRP 90, 672–676.

[8] Meike, D., 2013. Increasing Energy Efficiency of Robotized Production Systems in Automobile Manufacturing. PhD Thesis. Riga, 1–214.

[9] Borcherding, H., Austermann, J., Kuhlmann, T., Weis, B., Leonide, A. Concepts for a DC network in industrial production. 2017 IEEE Second International Conference on DC Microgrids (ICDCM), 227–234.

[10] ZVEI & consortium DC-INDUSTRIE2, 2022. System concept DC-INDUSTRIE2. https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2. Accessed date: 15.11.2022.

[11] Shuai, Z., Fang, J., Ning, F., Shen, Z.J., 2018. Hierarchical structure and bus voltage control of DC microgrid. Renewable and Sustainable Energy Reviews 82, 3670–3682.

[12] Meng, L., Dragicevic, T., Vasquez, J.C., Guerrero, J.M., 2015. Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC–DC Converters. IEEE Trans. Smart Grid 6 (6), 2615–2626.

[13] Bianchini, I., Kuhlmann, T., Wunder, B., Unru, A., Sauer, A., 2021. Hierarchical Network Management of Industrial DC-Microgrids. 2021 IEEE Second International Conference on DC Microgrids (ICDCM), 1–6.

[14] Dragicevic, T., Lu, X., Vasquez, J., Guerrero, J., 2015. DC Microgrids–Part I: A Review of Control Strategies and Stabilization Techniques. IEEE Transactions on Power Electronics 7 (31), 4876–4891.

[15] Nutkani, I.U., Peng, W., Loh, P.C., Blaabjerg, F., 2014. Autonomous economic operation of grid connected DC microgrid. 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 1–5.

[16] Zhao, P., Liu, Z., Zhao, Y., Wang, Q., Liu, J., 2021. An Adaptive Piecewise Droop Control Strategy for DC Microgrids. 2021 IEEE Fourth International Conference on DC Microgrids (ICDCM), 1–6.

[17] Nasirian, V., Davoudi, A., Lewis, F., Guerrero, J., 2016. Distributed adaptive droop control for DC distribution systems. 2016 IEEE Power and Energy Society General Meeting (PESGM), 1–13.

[18] Olives-Camps, J.C., Del Rodríguez Nozal, Á., Mauricio, J.M., Maza-Ortega, J.M., 2022. A model-less control algorithm of DC microgrids based on feedback optimization. International Journal of Electrical Power & Energy Systems 141, 108087.

Biography

Isabella Bianchini (*1990) studied electrical engineering at Pavia University, Italy. Since 2019 she has been a research associate at the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart. Her research focus includes industrial energy flexibility, demand response, and control of DC microgrids.

Jonas Knapp (*1994) studied engineering cybernetics at University of Stuttgart, Germany. Since 2021 he has been a research associate at the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart. His research focus includes modelling and simulation of industrial power grids, control design of DC microgrids, and potential analysis of electrical energy grids.

Simon Riethmüller (*1993) studied mechatronics engineering at Baden-Wuerttemberg Cooperative State University Stuttgart campus Horb, Germany. Since 2021 he has been project manager for the research project DC-INDUSTRIE 2 at HOMAG GmbH Schopfloch, Germany. His focus in the project includes the coordination of build up and start up the model plant provided by HOMAG for the research project and the coordination of tests at the plant.

Thorben Kwiatkowski (*1994) studied mechatronics engineering at Baden-Wuerttemberg Cooperative State University Stuttgart campus Horb, Germany. Since 2020, he has been an automation developer in the product development department at HOMAG GmbH. His main areas of expertise include PLC programming, virtual modelling, and the development of project and ramp-up tools.

Xiaotian Yang (*1993) studied electrical engineering at RWTH Aachen University, in Germany. Since 2020 he has been a research associate at the Fraunhofer Institute for Integrated Systems and Device Technology IISB. His research focus includes modelling and control of power electronic converters in the context of DC microgrids.

Alexander Sauer (*1976), Prof. Dr.-Ing. Dipl.-Kfm., studied mechanical engineering and business administration at RWTH Aachen University and received his PhD at the RWTH Aachen University. He is head of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart and head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart.