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Modular Stacked DC Power System for Offshore Electrification

Martin Tomren

Master of Energy and Environmental Engineering
Submission date: December 2013
Supervisor: Tore Marvin Undeland, ELKRAFT
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Problem description

A system level model of the Modular Stacked DC (MSDC) concept will be developed based on descriptions in patents and articles on the subject.

A case study will be performed to evaluate the available solutions for a stepwise expansion of an MSDC transmission and distribution system. The case study examines how the four oil and gas fields comprising Utsira High can be supplied with power from shore.

Abstract

Modular Stacked DC (MSDC) is an electrical system architecture intended for use in offshore petroleum installations. The system is patented and announced by GE Oil and Gas, but has currently not been built for a full scale installation.

This report describes the system architecture, significant components and functionality based on available publications.

Further, the report illustrates how an MSDC system can be built in a stepwise expansion program to complete a network of interconnected oil platforms receiving power from shore. This illustration is performed using the cluster of oil and gas fields named Utsira High in a case study, under the assumption that MSDC is chosen as the technological solution to deliver power from shore.

A software simulation model is built to represent a generic MSDC system. The model is employed to recreate some of the functionality described in the available publications. Several claims presented in patents and articles have been confirmed within the limits of a simulation model.

Preface

I must express my gratitude to a number of people who have contributed their work and time, and influenced this thesis.

I would like to thank Professor Tore Undeland for bringing together the group of people necessary to begin this thesis process, and for following it through to completion.

I would also like to thank Christof Sihler and Thiwanka Wijekoon of GE Global Research for bringing their work to the University, for presenting their technology, and for proposing what would become part of the problem description.

I would like to thank Salvatore D’arco of SINTEF for his invaluable help with the further development of the problem description.

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Contents

1 Introduction

1.1 Background and motivation

Several oil and gas fields on the Norwegian continental shelf are currently operated with, or are in the process of developing solutions for power-from-shore. The power transmitted from the national grid to an offshore installation will replace power generated from on-board gas turbines.

The operators of a field possess economic incentives to develop solutions for power from shore. Petroleum activity in Norwegian territory is subject to taxation and quotas on carbon dioxide (CO_2) emissions. In addition, the fuel costs of natural gas and diesel can be significant, and although a solution with power from shore is typically more expensive in terms of initial investments, the reduced energy cost over the lifetime of an installation can make the investment profitable.

Government licenses to develop and operate a petroleum field can include requirements to use power from shore. The Norwegian government has put forth national targets for CO_2 emissions, and the petroleum industry is a significant contributor to total emissions. New power demand will further motivate to increase investments in new renewable energy production, thus transferring funds from the Scandinavian market for green certificates to projects inside Norway.

The established technologies for power-from-shore are AC with long step out (Martin Linge) and HVDC point-to-point transmissions. Costly components in these systems include the subsea cables and converter stations. Moreover, a small number of manufacturers control a large majority of this market. Significant manufacturers of converter stations include ABB and Siemens.

GE Oil and Gas is motivated to enter the market to supply converter stations. They also hope to promote their own brand of connectors. GE Oil and Gas has proposed and patented the MSDC solution. The solution aims to reduce the combined cable costs in the transmission and distribution system, thereby making GE Oil and Gas more cost effective than its competitors.

The MSDC architecture has not been tested on a full scale, which means that it lacks operational experience, and it has not been qualified according to current standards. Furthermore, no sales have yet been announced.

2 References

[1] Datta, Rajib, Christof Martin Sihler, and Richard S. Zhang. "DIRECT CURRENT POWER TRANSMISSION AND DISTRIBUTION SYSTEM." U.S. Patent No. 20,080,284,249. 20 Nov. 2008.

[2] Shiler, Christof, Rajib Datta, and Robert Roesner. "MVDC power transmission system for sub-sea loads." European Patent No. EP 2071694. 17 Jun. 2009.

[3] Zhang, Richard S., et al. "Modular stacked subsea power system architectures." U.S. Patent No. 20,100,133,901. 3 Jun. 2010.

[4] Sihler, Christof Martin, et al. "HVDC POWER TRANSMISSION WITH CABLE FAULT RIDE-THROUGH CAPABILITY." U.S. Patent No. 20,120,268,099. 25 Oct. 2012.

[5] Schroeder, Stefan, Christof Martin Sihler, and Sebastian Pedro Rosado. "METHOD AND SYSTEM FOR CONTROL POWER IN REMOTE DC POWER SYSTEMS." U.S. Patent No. 20,120,161,518. 28 Jun. 2012.

[6] Sihler, Christof Martin. "Modular Stacked Power Converter Vessel." U.S. Patent No. 20,120,057,308. 8 Mar. 2012.

[7] Song-Manguelle, J.; Datta, R.; Harfman Todorovic, M.; Gupta, R.; Zhang, D.; Chi, S.; Garces, L.; Lai, R., "A Modular Stacked DC transmission and distribution system for long distance subsea applications," *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE* , vol., no., pp.4437,4444, 15-20 Sept. 2012

[8] Sihler, Christof Martin, Simon Herbert Schramm, and Stefan Schroeder. "DISTRIBUTED DC ENERGY STORAGE FOR SUPPLYING AN INTERMITTENT SUBSEA LOAD." U.S. Patent No. 20,130,026,831. 31 Jan. 2013.

[9] Lai, Zhang, Todorovic, Garcés, Gupta, Chi, Dong, Sihler, Gunturi, Rocke, Elgsaas, Datta, Song-Manguelle, Alford, Haji, Pappas. "Modular Stacked DC Transmission and Distribution System for Ultra-deepwater Subsea Process." 2013 Offshore Technology Conference. 2013.

[10] Statoil. "Utsirahøyden Elektrifiseringsprosjekt - etablering av infrastruktur for kraft fra land til felt på Utsirahøyden. " DOC-UHP-00001. March 2012

[11] DET NORSKE VERITAS AS. "Electrical Power Cables in Subsea Applications." DNV-RP-F401. February 2012

[12] "Edvard Grieg feltdata." Accessed 2013-12-13. http://www.offshore.no/Prosjekter/Olje-felt-informasjon.aspx?navn=EDVARD+GRIEG

[13] "Ivar Aasen feltdata." Accessed 2013-12-13. http://www.offshore.no/Prosjekter/Olje-felt-informasjon.aspx?navn=IVAR+AASEN

[14] "Gina Krog feltdata." Accessed 2013-12-13. http://www.offshore.no/Prosjekter/Olje-felt-informasjon.aspx?navn=GINA+KROG

[15] "Johan Sverdrup feltdata." Accessed 2013-12-13. http://www.offshore.no/Prosjekter/Olje-felt-informasjon.aspx?navn=JOHAN+SVERDRUP

[16] "CO2-avgift." Accessed 2013-12-13. http://www.regjeringen.no/templates/RedaksjonellArtikkel.aspx?id=558367&epslanguage=NO

3 Description of MSDC topology

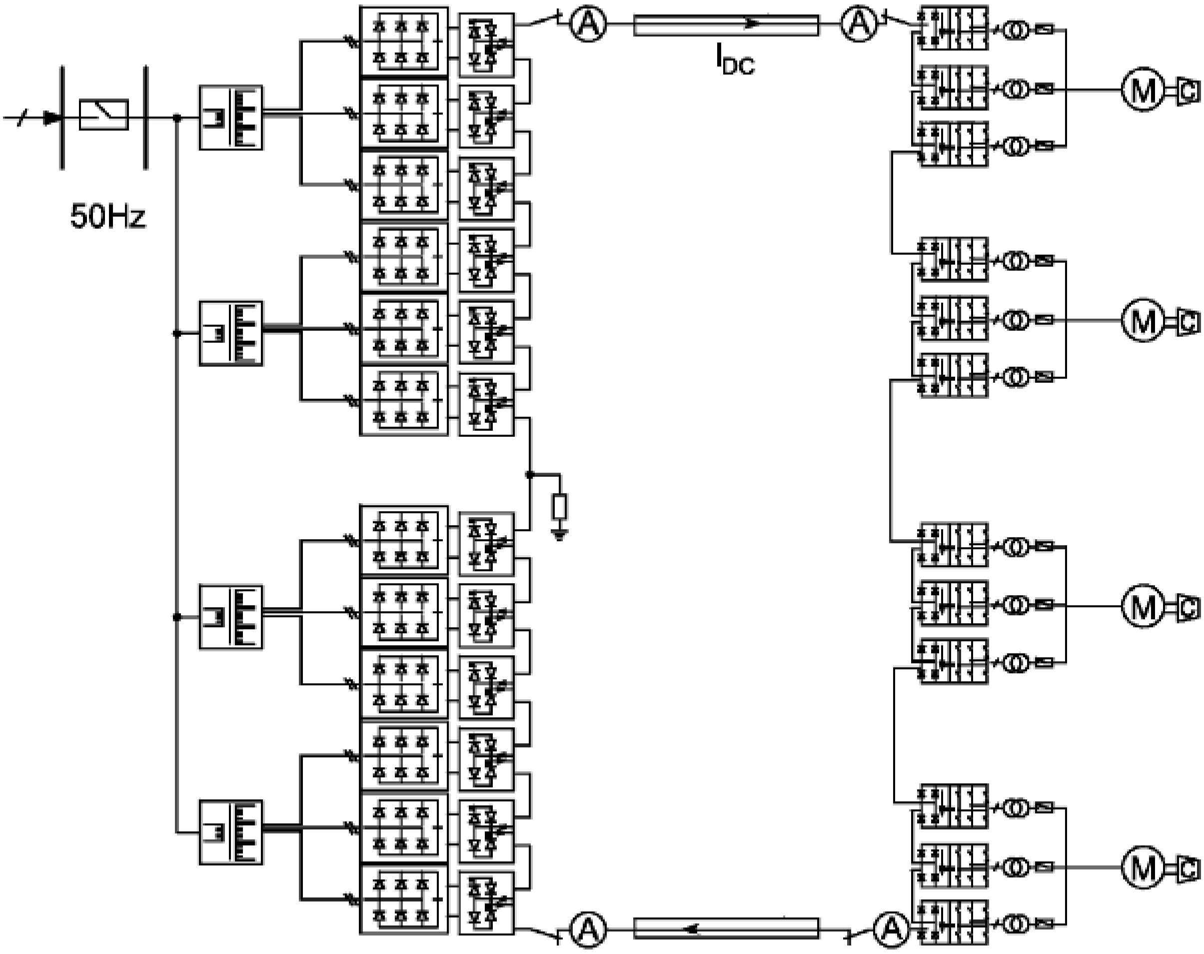


Figure 1 – MSDC architecture as described in [4].

The Modular Stacked DC (MSDC) architecture has been proposed and patented by GE Global Research. It is described in a series of patents, published articles and conference papers. All publications regarding this topology have been written by employees of GE, and it has not been possible to obtain any papers written by independent researchers.

The topology is presented as a solution for providing electric power to offshore and subsea oil and gas instillations; it serves the purpose of a transmission and distribution system. Similar topologies have also been presented by GE to use in wind and photo voltaic industries. In these last two applications, the technology is applied as a collection grid. The MSDC name is not utilized in these two applications.

The MSDC topology differs from conventional HVDC in the following ways. First, as opposed to point-to-point transmission, the DC grid is organized in a ring/loop form with several converter substations. Second, as opposed to parallel connected in an AC distribution network, multiple loads are series connected in the DC network. Finally, as big compressor and pump loads are directly connected, the DC ring/loop acts as both a transmission and distribution network, thus replacing an AC distribution.

The converters are built as a modular design on multiple levels. Several converter stations are series connected to the same loop. Each converter station contains multiple sub-modules of identical converter packs. Each sub-module can also be divided into three distinct sections, which respectively serve the purpose of a chopper, DC link, and inverter/rectifier.

The patents and articles published by GE emphasize specific features of the topology. The publications highlight the reliability and redundancy in converter stations against both internal and external faults. Additionally, the modular design contributes to the redundancy and facilitates the replacement of components.

The articles consistently illustrate a detailed description of the converter stations and their interior circuit diagrams. In particular, they focus on the control mechanisms, switching patterns, and the protection mechanisms and fail-safes built into each converter station.

3.1 Component description

3.1.1 Converters

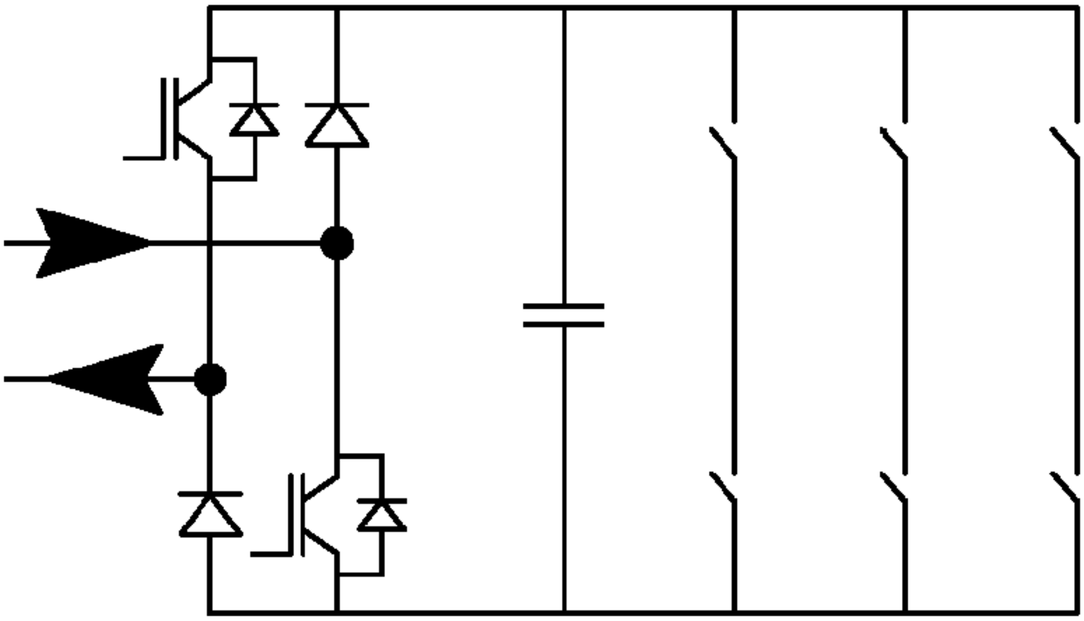


Figure 2 – Converter sub-module as illustrated in [1].

The switched power electronic converters suggested for use in a MSDC system are described in significant detail in patents and articles [1-9]. The authors emphasize such features as a high level of redundancy the modular design. Redundancy is frequently highlighted because any halt in production will result in severe economic losses for the operators of oil and gas installations, and also because the converters are intended to be located subsea the time it would take to access and service a component is significant.

Several alternative implementations are possible, and all share some common characteristics. The modular nature of the topology, for instance, means that a single converter station can consist of any number of series connected (stacked) sub-modules. The common building blocks comprising a sub-module are a DC-DC chopper, a capacitor, and a DC-AC inverter/rectifier.

A notable element of the system design is the fact that source converters and load converters share a very similar topology, even though they have different requirements and control strategies. The source converter draws power from an AC grid or generator(s). An AC-DC rectifier step maintains the charge of a capacitor. A DC-DC chopper feeds power to the main transmission loop in the system. A load converter draws power from the main transmission loop through a DC-DC chopper that maintains charge of a capacitor. A DC-AC inverter supplies downstream 3-phase loads with an appropriate voltage and frequency.

The various patents and papers describing the technology mention multiple alternative implementations of converter stations. For example, the article [7] proposes to use 3-level converters employing 12-pulse rectifiers in source converters and Neutral Point Clamped inverters in load converters. Further, the patent [1] mentions an alternative implementation wherein several DC-DC choppers are series connected to supply a single capacitor, and where multiple inverters can be parallel connected to draw power from a single capacitor.

The patent [1] notes the fact that the source converter can be any other type of appropriate AC-DC converter capable of producing a variable voltage, including thyristor based line commutated converters.

The source converter uses feedback control to regulate the target parameter current on main loop, and is realized by applying the output from the regulator to adjust the duty cycle of the chopper circuit. The load converters use feedback control to regulate the target parameter voltage over the internal capacitor, and are similarly realized by adjusting the chopper duty cycle. The inverter uses a separate control system, typical of any motor drive application.

The most common design suggested in the cited literature for the DC-DC chopper is a half-bridge (Figure 1) with two fully controllable power electronic switches (IGBT, GTO or similar) and two power diodes. During normal operation, the circuit alternates between two switching states: When both switches are open the loop current will be conducted via the diodes through the capacitor to charge it, thus increasing the capacitor voltage. When one of the switches is closed and the other is open the loop current will bypass the DC-DC chopper. This switching state will not contribute to changing the capacitor voltage. A third switching state exists, but is only applied when an overvoltage is measured over the capacitor: Both switches can be closed simultaneously, causing the loop current to be conducted through the capacitor from negative to positive terminal. This current flow reduces the capacitor voltage. Application of this switching state reverses the power flow in the system, for example in a situation where a motor load requires electromechanical breaking [1]. This switching state is also useful for discharging the capacitor during a rapid shut down after detecting a fault, as described in [1].

The DC-DC chopper has two different switching states that both bypass the loop current without any transference of power. The two switches can be controlled to close alternatingly thus distributing switching losses and on-state losses evenly between them. In the case where one of the switches should fail and leave the faulted device to behave as an open circuit, the remaining switch can ensure the continued operation of the sub-converter, as long as this is within the thermal limitations of the device. This feature adds to the redundancy of the converter design [1]. The functionality of reversing power flow is lost with the failure of one switch.

Theoretically, the topology could in use any load converter and control it to supply power to the transmission loop, for example if a platform that is typically a consumer of electricity is required to supply power to other parts of the network. This functionality is however not described in any of the cited literature.

The functionality of reversing power flow is not typically required in subsea loads. These loads are mostly pumps and compressors and will typically not change direction of torque or angular velocity. If the converter does not require to be designed for reversible power flow, the DC-DC chopper can be simplified. The number of components per sub-module can be reduced from two controlled switches and two diodes to a total of two components. The patent [1] suggests two alternative designs. The simplest design shown in Figure 3 requires only one controlled switch and one diode. While the switch is open the capacitor is charging, and while the switch is closed the current is bypassed. The redundancy of the half-bridge topology is lost, but the complexity of components is halved. The other alternative design shown in Figure 4 replaces the diode in the above circuit with another controlled switch. The circuit is identical to the one found in a sub-module of an MMC converter. The reason the MMC requires two controlled switches is because the direction of current in the sub-module will alternate during operation. In the MSDC architecture the current is unidirectional and the additional switch adds complexity without additional any functionality.

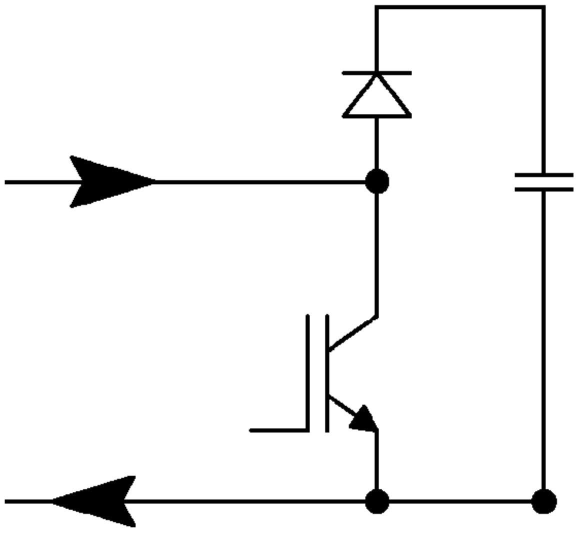


Figure 3 – Alternative chopper design #1.

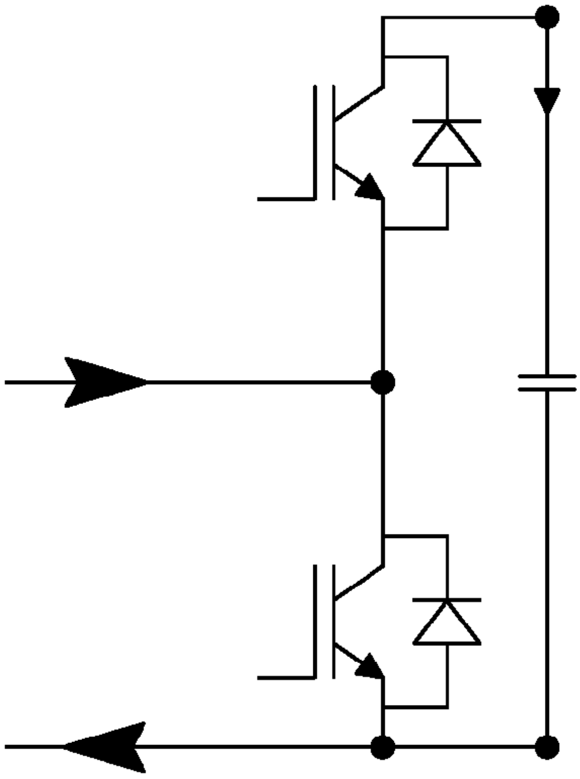


Figure 4 – Alternative chopper design #2.

3.1.2 Cable

The choice of cable technology for the main transmission loop is not described in detail in the cited documentation. The patent [1] suggests the use of polymer cables, particularly EPR. The patent also claims that any type of cable capable of sustaining a DC voltage can be used. Based on descriptions of other components, operational modes and control strategies, one can identify certain defining features and requirements of the cable.

One defining feature is the fact that all cable segments on the main loop has identical requirements for current carrying capacity and insulation level. All segments can consequently use the same cross section design.

The intended applications require the cable to be designed for subsea environments. This typically suggests a single core design with the inclusion of wound armor and a water tight seal in the form of metallic sheaths.

The magnitude of current in the cable is equal for all load conditions. For a given maximum system voltage, the magnitude is set to the current value required to supply the maximum load scenario. This means the cross section area of the cable must be dimensioned according to constant maximum power loss. The effective cross section area of a cable is proportional to the amount of (and cost of) the conductor material copper, and inversely proportional to the resistance per kilometer, and thus also the operational losses. The most economically beneficial solution is found by selecting a cross section area where the marginal cost related to manufacturing and installation of the cable is equal to the marginal savings of reducing power losses over the expected lifetime of the installation at present discounted value.

Another conclusion that can be drawn from the constant current design is that the operating temperature of the cable will be constant. The absence of temperature variations will reduce stress from thermal expansion in cable elements. High operating temperature increases the copper resistance and contributes further to increasing the maximum temperature at sustained operation. The high operating temperature must be accounted for when estimating losses in the design phase. Special care must be taken if one is considering burying or trenching the cable because sand, rocks and sediments act as thermal insulators around the cable and will increase the maximum operating temperature.

Although the cable carries a direct current, there will be a significant voltage ripple near all converter substations. The distributed parameters in cables cause the voltage ripple to reduce with distance from converters. Although a voltage ripple does not pose any obvious obstacles in terms of cable or connector design, the patent [1] does open for the option of including a reactor in the load converter. The addition of reactors will alter the effective L/R ratio of the transmission circuit, and this can be used to affect the stability of the system. Additional component will be avoided if possible to reduce the complexity and cost of subsea equipment.

The choice of insulation material is left open in the cited literature. Extruded insulation has become a favorable solution for subsea HVDC transmissions and is increasingly applied to oil and gas installations with power from shore. Mass impregnated paper insulation is another alternative, as demonstrated on Valhall. Regardless of insulation system, the constant current design helps to alleviate the obstacle of thermo-mechanical fatigue that will occur under cyclic operating temperatures. Cyclic temperatures cause cable materials inside the sheath to alternately expand and contract in radial direction, resulting in significant strain [11].

When choosing the insulation level, one must take into consideration the desired operating modes and desired functionality. If one chooses half the pole-to-pole voltage, the system can deliver half rated power in monopole operation. The voltage to ground can change during operation modes, depending on where the grounding point is located and whether the point can be moved/controlled. Patent [4] specifies insulation level should be equal to the pole-pole voltage, meaning double the voltage required for ideal operation in a balanced state at rated power.

The patent [4] describes how electrode arrays can be used to manipulate the system potential difference to ground. Electrode arrays can open new conductive paths, and provide protection mechanisms against cable faults.

If signals are to be transmitted between converters as described in [7], fiber optic strands must be included either in the interior of the cable or alongside the cable exterior.

3.1.3 Connector discussion

The connectors linking segments of cable to substations are suggested to be wet mated [1], meaning they can be connected while immersed in water. The process involves expelling the conductive water trapped between mating components by several steps of flushing and finally filling the volume with dielectric oil. GE Oil & Gas manufactures its own brand of wet mated connectors under the name MECON. It has been installed and operated on AC installations since 2001. Plans have been indicated to further develop the concept with wet mated DC connectors.

The patent [1] also mentions the option of using dry mated connectors. The installation process involves mating two cable ends to a substation above sea level before lowering the completed assembly down to the sea bed. In the event a substation would require maintenance or replacement, the complete assembly including cable segments would be brought up to surface level. Compared to a solution with wet mating, this solution adds the requirement for the cable segments near the substation to be designed to endure the dynamic stresses involved with installation/maintenance. The solution also requires longer cables for the purpose of raising the installation to the surface. The additional costs resulting from longer dynamic cables suggest that dry mated connectors are only economically feasible in shallow water installations.

3.1.4 Switchboards and protection mechanisms

Switchboards are important for the protection of the system. They are installed to bypass a faulted sub-module and to disconnect feeders to the sub-module, thus isolating the fault from the remaining system. A bypass switch will be located on the loop side of each converter station. Although the system carries direct current on the main transmission loop, the design and architecture has eliminated the need for DC circuit breakers [1][4].

3.2 Control strategy

The control strategy is implemented on several levels within the system. Multiple controllers are distributed between the converter stations in the circuit.

The feedback controller in the source converter operates to regulate the loop current to the reference value using a PI regulator. The feedback controller in each load converter regulates the capacitor voltage to the reference value. A PI regulator determines the duty cycle of the converter, and this duty cycle is used to determine commutation of power electronic switches. The commutation of several stacked sub-modules will be coordinated and phase shifted to minimize the total harmonic distortion measured over the stack.

Real time measurements are necessary to perform the function of the feedback controllers. It is necessary to measure loop current at the source converter, and to measure the capacitor voltage in each sub-module in each load converter.

3.3 Applications

The following chapter proposes a number of offshore applications where an MSDC system as described in literature could meet the requirements.

The MSDC can be built as a point-to-point transmission link, either between shore and a platform, or between to platforms. Since the transmission link operates with direct current, the AC grids at the two installations can employ different frequencies (50/60 Hz) and are not required to be synchronized. The direction of power flow can be either unidirectional or reversible depending on the choice of either diode rectifier or controlled rectifier respectively.

MSDC can be employed to distribute power to various loads surrounding an oil platform. The loads are tie-backs to a platform and located subsea. Typical loads are large compressors and pumps.

MSDC can be built as a combined transmission and distribution system, used both for transmitting power from shore to an oil field, and for distributing the power to multiple loads including one or several oil platforms and the surrounding subsea installations. The architecture with a single source converter on shore and multiple loads offshore is equally applicable to a shore-to-subsea installation without any platform.

MSDC can be built as an offshore grid between multiple installations. With converters built for two way power flow, a single installation can alternate between receiving and contributing power to the grid depending on available generation capacity and demand. Power sharing will be enabled between the installations comprising the grid. Multiple converters operating as sources will have to coordinate their production to match the power demand, either by designating a single swing bus and operating the others at constant power, or by using current droop to regulate multiple source converters simultaneously.

The MSDC topology is well suited to run transport compressors for a petroleum pipeline. The power cable can be laid in a trench parallel to the pipeline, and multiple stations for recompression can be distributed along the length of the pipeline. Each station will have a separate Variable Frequency Drive (VFD) built into the MSDC converter.

3.4 Possible challenges with MSDC

With a conservative approach the insulation level of components connected to the main loop or to the converter circuit must be chosen as the pole-to-pole voltage of the transmission cables. This includes components such as connectors, switchgear, DC-DC chopper, capacitor, inverter, transformer and any motor connected directly to an inverter. The maximum potential difference from conductor to true ground can be in the range of several hundred kV, and this voltage is much higher than would be measured between two points in the circuit of a sub-module. Challenges can arise to find component classified for this insulation regime.

If converter stations are to send and receive signals and commands, fiber optic strands must be installed parallel to each cable conductor segment. The fiber optic can be included internally in the cable, but single core cables does not have much available space where the fiber optics can be located. The termination of the cable is challenging if it involves fiber optics, and a challenge is presented if the signal should alter route in the event a converter station would be bypassed by switchgear. A tripped converter cannot be expected to continue relaying the signals. Another alternative is to lay a dedicated fiber optic cable next to the power cable, but this way the fiber optics are not protected by the armor wires of the power cable and is vulnerable to damage from the surrounding environment.

The switching operation in each converter station causes significant voltage ripple. This ripple will be observed on adjacent connectors and will extend over the lengths of cable closer to the convert station. If it is found necessary to reduce this ripple, [1] suggests installing reactors in each converter station. To add a component to a subsea installation will increase the cost of the project as it adds to complexity, requires pressurized housing, and requires qualification for the subsea environment.

System transients and changes in power demand will cause the cables on the main loop to undergo rapid changes in potential difference to ground. Existing standard and test requirements for subsea cables have not been written with variable voltage HVDC in mind. The effect of these voltage changes can be difficult to predict.

If a large motor on-board a platform is operated directly from the MSDC converter (instead of from a VFD connected to the main AC grid) it will not be able to receive power from backup generators. This connection cannot be used for critical components such as fire water pumps.

The cables on the main loop conduct direct current and are intended to be laid as single conductors (as opposed to pairs conducting current in opposite directions). The cables will create a significant magnetic field when energized. Such magnetic fields are known to affect compasses on ships.

The use of series connected converters makes the system vulnerable to failures to faults on cables and connectors. Any service or modification work on equipment that cannot be isolated from the system by switchgear will require the entire transmission system to shut down for the duration of the work. In addition, wet-mated connectors for HVDC lack operation experience. If MSDC shall see commercial success, these limitations must be found acceptable or somehow mitigated by altering the design.

MSDC is presented as a solution for combined transmission and distribution of power to offshore installations. The main competing technology is HVDC transmission with an AC distribution grid. Another competing technology is AC with long step-out. If MSDC as described in the publications is to be more cost efficient than the competing technologies, a number of criteria must be fulfilled. Firstly, the transmission distance from shore must be long enough to justify using a direct current, but simultaneously short enough to accept any additional cost of increased cable cross section and operating costs of maximum current. Secondly, the number of separate loads and the distances between them must be large enough to make the savings of using MSDC cabling will outweigh any other additional costs of using MSDC. When calculating and comparing the total cable cost of different technologies, it is advantageous for MSDC if the multiple loads are somewhat equal in power requirements, rather than having one large load and many small.

3.5 Comparison with existing technology

The following describes advantages and disadvantages of employing a system using MSDC technology both for transmission and distribution to multiple subsea loads. The system is compared with a solution of HVDC transmission and AC for distribution to subsea loads. Cables and converters are considered critical for the success of MSDC.

Table 1 – Comparison of MSDC and conventional HVDC with AC distribution

	Advantages of MSDC	**Disadvantages of MSDC**
Cable cost	Shorter and fewer cables in distribution network reduces installation cost.	Large cable cross section (including in distribution cables) can increase manufacturing cost.
Connector cost		Wet maters required to achieve savings in cable costs.
Cable and connector reliability		Series connected loads. High number of wet maters. Wet maters for DC are not a mature technology.
Cable and connector service and maintenance		Altering the main circuit requires entire system to shut down.
Converter cost	Reduces number of VFDs required in AC network.	Multiple converter stations. Placement of converters subsea. Requirements to insulation level.
Converter reliability and redundancy	Bypass functionality. Modular design provides backup capacity. Redundant against single IGBT failure.	Sub-module serving as VFD cannot receive power from backup generators.
Converter service and maintenance	Modular design implies a faulted sub-module can be readily replaced.	Subsea placement renders converters inaccessible.

Several of the advantages of using the MSDC architecture are related to the converter design. The total cable cost will vary significantly between projects, and if conditions are favorable and the cable savings are substantial, MSDC can become the profitable solution for a given project. Whether or not MSDC will be built on a full scale project will depend upon whether the risk related to cable and connector reliability is found acceptable or not.

4 Expansion case study

4.1 Introduction to Utsira High

In this thesis, Utsira High is used as a case for investigation and analysis.

The Utsira High is the name used for a group of four oil fields currently under development in the North Sea. The fields are:

- Edvard Grieg, formerly Luno
- Ivar Aasen, formerly Draupne
- Gina Krog, formerly Dagny (developed with a connection to the Eirin subsea field)
- Johan Sverdrup, formerly Avaldsnes and Aldous

Production of the various platforms is scheduled to begin during 2015-2018 [12][13][14][15]. All fields are proposed to use a common solution for power-from-shore with a single HVDC transmission link from Kårstø and distribution cables between the platforms [10].

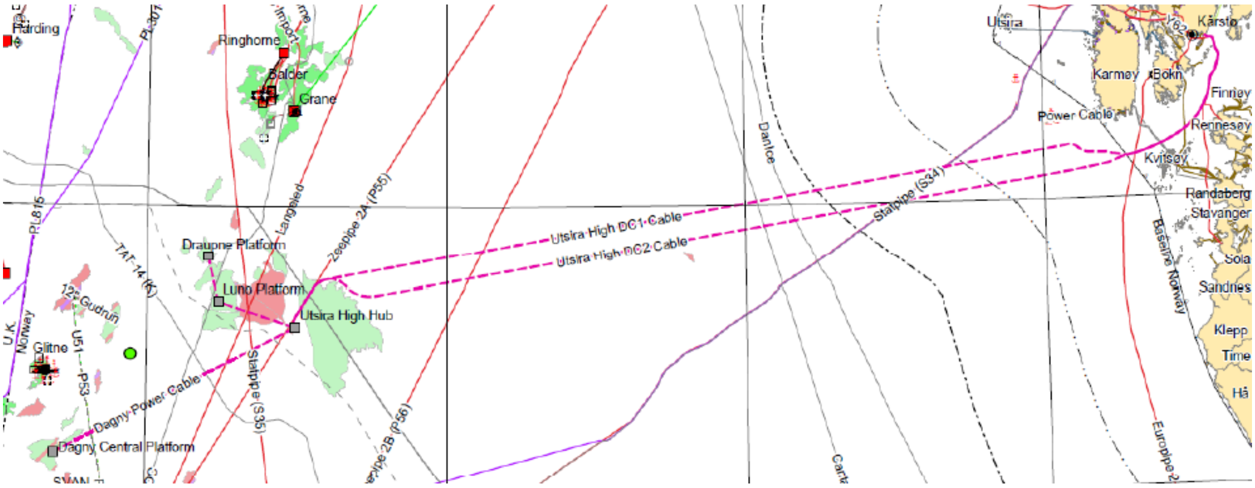


Figure 5 – Map over Utsira High and Kårstø with cable paths drawn as suggested by Statoil. Source: [10].

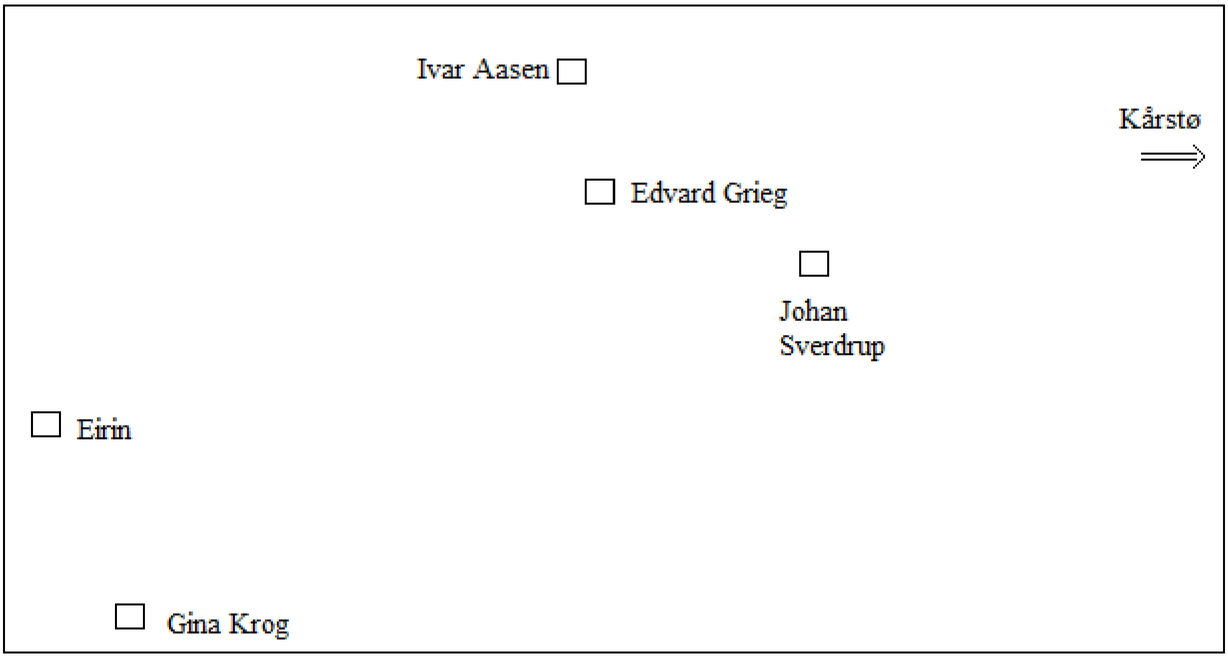


Figure 6 – Locations of oil and gas fields at Utsira High.

4.2 Actual solution and schedule

The first platforms scheduled to start production are Edvard Grieg in 2015 and Ivar Aasen in 2016. Edvard Grieg will in its first years of operation be self-supplied with power from on-board generators. The platform will be built with enough generator capacity to cover both its own and Ivar Aasen's power requirements. Ivar Aasen will be built with only emergency generators and will require an external power supply to cover non-essential loads. In the time following completion, Ivar Aasen will receive power from generators on Edvard Grieg through a platform-to-platform AC cable link.

Gina Krog is scheduled to start production in 2017, while Edvard Grieg is scheduled for 2018. Both platforms are planned with a power system capable of receiving externally generated power from sub-sea cables. Information on planned on-board generating capacity on Gina Krog and Edvard Grieg is not available at this time.

Later, if the government chooses to mandate it, a power-from-shore system will be built to supply all four platforms with power from a shared transmission and distribution system. The transmission will be an HVDC system with converter stations at Kårstø and at a dedicated Hub platform located near Johan Sverdrup. A high voltage AC network will distribute power from the Hub to the platforms, and the previously built link between Edvard Grieg and Ivar

Aasen will become part of this distribution network. After the completion of the power-from-shore system, on-board generator capacity, such as on Edvard Grieg, will be reserved for events where shore power is unavailable.

4.3 Assumptions for a case study of MSDC

To propose how Utsira High can be built with MSDC some alterations to the actual development plan must be made.

It will be assumed that the decision to employ MSDC is made at an early stage of development, before the design of the first platform (Edvard Grieg).

Instead of locating the complete load converter at a dedicated Hub platform, converter stations must be distributed amongst the platforms. It will be assumed all platforms are either commissioned with converter stations or prepared to be retrofitted.

The case study will assume that electrode array are approved and licensed by the government, and that the corrosion issues related to electrode arrays can be solved.

The following criteria and goals are assumed to aid the decision process where multiple solutions are viable: The plan should be formulated in multiple steps, where each step adds some functionality and builds towards completing a full scale system for power-from-shore. The plan should be alterable, to account for the fact that some platforms are under construction before the final decision has been made on whether to mandate the use of power-from-shore. Two goals are presented, and assumed desirable to achieve both after completing each step and after the completion of the full system: Firstly, the system should be reliable and have backup solutions in case of component failure elsewhere in the system. Secondly, the chosen solutions should aim to minimize costs, particularly demonstrated with cable cost.

4.4 Proposed solution

4.4.1 Step 1 – Connecting Edvard Grieg and Ivar Aasen

Edvard Grieg and Ivar Aasen are the first platforms to start production. Their power systems are designed to be closely interconnected and interdependent. For these reasons, the first step in developing an MSDC transmission and distribution system on the Utsira High will be to create a transmission link between these two platforms. Converter modules will be installed on both platforms. Converters on Edvard Grieg will be designed for both receiving and exporting power, and dimensioned for the largest demand among the two platforms. Converters on Ivar Aasen will be dimensioned to receive enough power for its own demand (or depending on the choices in Step 2 it could be built identical to converter on Edvard Grieg). At a later stage when power is available from shore, additional converter modules can be installed on Edvard Grieg if its power demand is higher than that of Ivar Aasen. Converters on Edvard Grieg require the additional measurements and control system functionality necessary to operate as the power source (swing bus) in an isolated system.

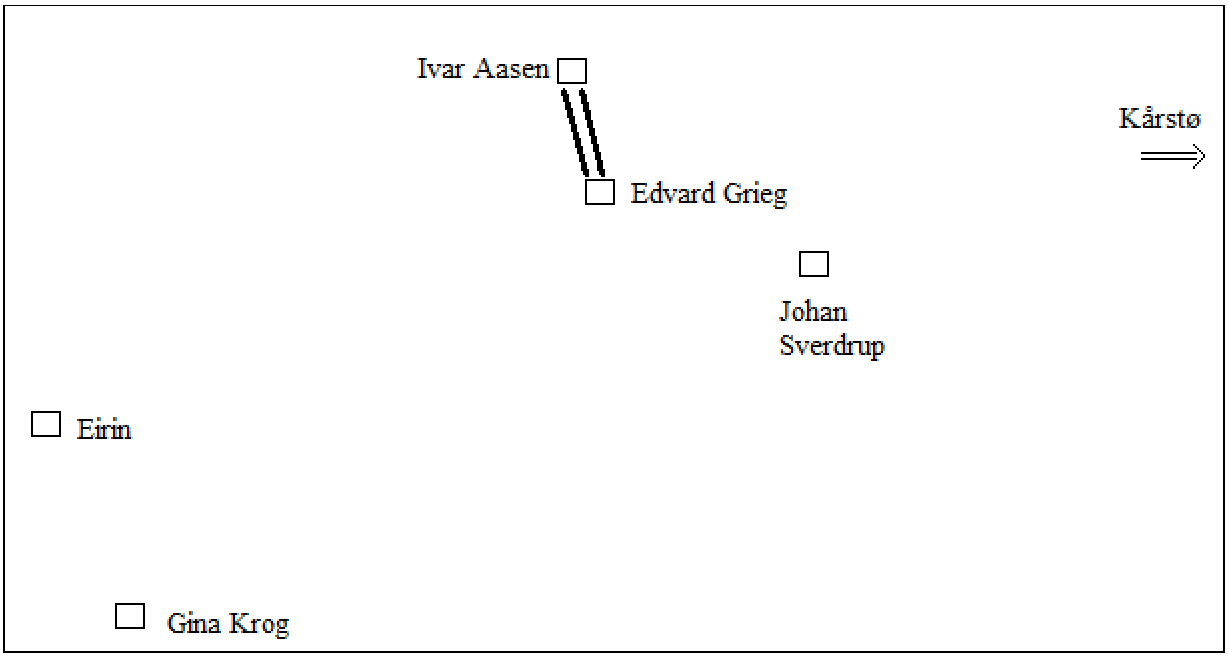


Figure 7 – Power system after completion of Step 1 in the expansion strategy.

Two DC cables will be installed between the platforms. The current carrying capacity and insulation level will have to be dimensioned according to the full scale system at the time of completion. The total power demand is estimated at upwards of 300 MW [offshore.no]. If choosing the rated current 1250 A (as is done for the simulation scenarios in chapter 5) this gives pole voltages +/-120 kV and insulation level 240 kV according to [4].

Since these cables can be connected in parallel in a later step, it is possible to construct these two specific cables to be rated at half the current rating of the complete system. This does however require double the amount of stacked converters in be installed on both platforms, and is therefore decided against. The cables between Edvard Grieg and Ivar Aasen will rather be built with the current rating of the full system. This will later provide redundancy against faults on any of the two cables.

The full capacity, however, will not be utilized when the power transmitted is only the consumption of Ivar Aasen. If operated at the rated current the copper losses in cables will be at a maximum (as rated), while only a small part of the insulation level is utilized. If the loop current can be lowered, the active losses will be reduced. A calculation example where 20% additional sub-module capacity is installed, the copper losses can be reduced to 70 % of rated losses. Since the power demand of platforms can be low early in the lifetime (due to high reservoir pressure), the loop current can be lowered while converters operate at near 100% duty cycle. Edvard Grieg and Ivar Aasen can also be fitted with extra converter modules, allowing the loop current to be lowered while transmitting the full power demand. Since the cable lengths are relatively short, the savings of reducing these losses are limited, and may not make the investment of extra converters profitable. However, if at a later stage the mandate of building power-from-shore is decided against, these calculations on cost must be repeated.

4.4.2 Step 2 – Shore power to Edvard Grieg and Ivar Aasen

A decision to use electrode arrays with full current carrying capability allows power to be transmitted over a single conductor. Assuming the combined power demand of Edvard Grieg and Ivar Aasen at this stage of the field lifetimes is less than half the total expected power demand of the completed installation, a single cable transmission will have the power capability to supply Edvard Grieg and Ivar Aasen from shore, regardless of choice of cable insulation level. If the use of electrode arrays were not approved, the completion of Step 2 would require two cables to shore.

The second Step in the expansion plan will therefore be to build one transmission cable to shore, a converter station at Kårstø, and two electrode arrays.

The modular properties of the converter can be used advantageously when dimensioning the equipment to be installed on Kårstø. At this step of expansion, the shore installation is only required to provide power for two platforms (Edvard Grieg and Ivar Aasen). The size and number of stacked sub-modules built at this stage can thus be limited. This way, some of the investment is postponed until a later step of expansion, and will reduce economic losses in the event Gina Krog and Johan Sverdrup would not be mandated to develop power from shore.

In development of Step 2 the decision will be made on placement of transmission cable termination and electrode array. Both Edvard Grieg and Ivar Aasen are viable options (both in this step of expansion and in regard to future development). The following must therefore be considered in the decision process:

- Security of supply to Ivar Aasen, in case of cable fault between Ivar Aasen and Edvard Grieg.
- Forms of island operation modes in the completed system, for example in case of fault on cables connected to Gina Krog.
- Current path in water when using electrodes as conductors. This variable will depend on whether it is acceptable that Edvard Grieg is in the current path between Ivar Aasen and Johan Sverdrup.

For the following discussion it will be assumed that security of supply is the most important criteria, thus the cable termination and electrode array will be placed at Ivar Aasen.

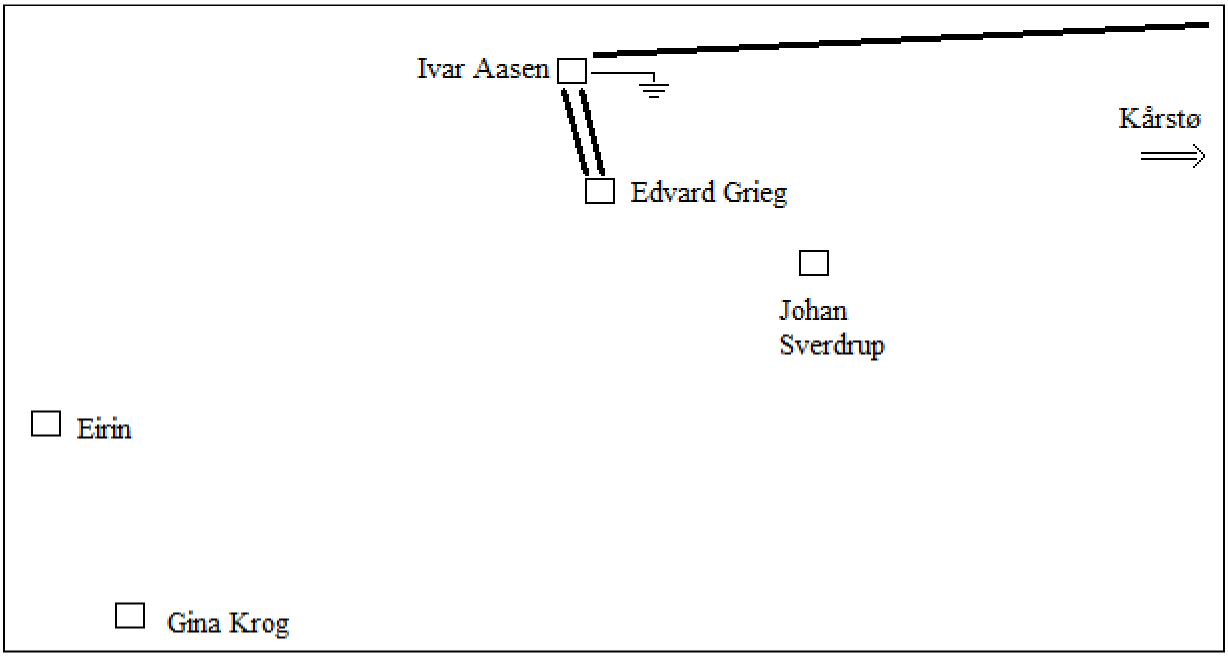


Figure 8 – Power system after completion of Step 2 in the expansion strategy.

The following operation modes are possible after the completion of Step 2:

1. During normal operation Kårstø will supply both Edvard Grieg and Ivar Aasen with power. The circuit is formed and current is transmitted from Kårstø through transmission cable to Ivar Aasen, further through one cable to Edvard Grieg, back through the other cable to Ivar Aasen, where the current passed to the electrode array, and conducted through water. The current return to Kårstø via the other electrode array near shore.
2. In case of a fault on a cable between the two platforms (distribution cable), Ivar Aasen will continue to receive power from shore, while Edvard Grieg will rely on on-board generators. Upon detecting the fault, switchgear on Ivar Aasen will isolate Edvard Grieg from the main circuit by shorting the terminals of the two platform-to-platform cables. Simultaneously the switchgear will connect the negative terminal of the converter module to the electrode array. If performed correctly, Ivar Aasen will continue to receive shore power uninterrupted. Note that no DC current is broken in the procedure, only redirected. Edvard Grieg will observe a rapid decline in cable current and is will start generators. Because of the time it can take to start additional generators, load shedding is probably necessary if blackouts are to be prevented. The platform could be reduced to only emergency power or a blackout. After generators are started, the platform can continue operations in island mode until the fault has been improved.
3. In case power from shore is unavailable, the system will return to an operation mode identical to the system in Step 1. This situation can be caused by a fault on a transmission cable or by unavailability of the Kårstø converter station. If the downtime is planned, the platforms can prepare for the change in operation mode by starting the necessary generators before performing a controlled transition to island operation. The switching procedure is performed at Ivar Aasen and involves shorting the transmission cable termination with the electrode array, while simultaneously connecting the secondary distribution cable to the terminal where the transmission cable was previously connected.

4.4.3 Step 3 – Including Johan Sverdrup and Gina Krog

Gina Krog is scheduled to start production in 2017 and Johan Sverdrup is scheduled for 2018. At the time when these platforms will be undergoing design and construction, it can be assumed that the decision has been made to mandate a power-from-shore solution for the whole of Utsira High. The two remaining platforms can be designed with shore power in mind, and the next step in expansion of the MSDC network can be chosen with the objective of optimizing the final completed design.

Step 3 is to connect the existing MSDC network to the remaining platforms, to build another electrode array, and to expand capacity on the Kårstø converter station. (The additional electrode array is optional, and can be substituted with an additional cable between Edvard Grieg and Johan Sverdrup.) Gina Krog is planned with a connection to the subsea field Eirin. A typical solution would be to install 3-phase AC cables between the platform and the subsea loads. An alternative solution is to include Eirin as a separate MSDC converter station. An Eirin converter station would minimize the amount of cables in the system, but would have disadvantages with respect to backup power in case of cable faults elsewhere in the system. Since much of the advantage of the MSDC system comes from reducing the number of and lengths of cables, it will be assumed the chosen solution for the remaining discussion.

When the insulation level is designed as pole-to-pole voltage, the system is capable of transmitting the full rated power while running with a single transmission cable and conducting electrodes. When Step 3 is completed, all platforms will be fully supplied with power-from-shore.

Two options are available as network topology:

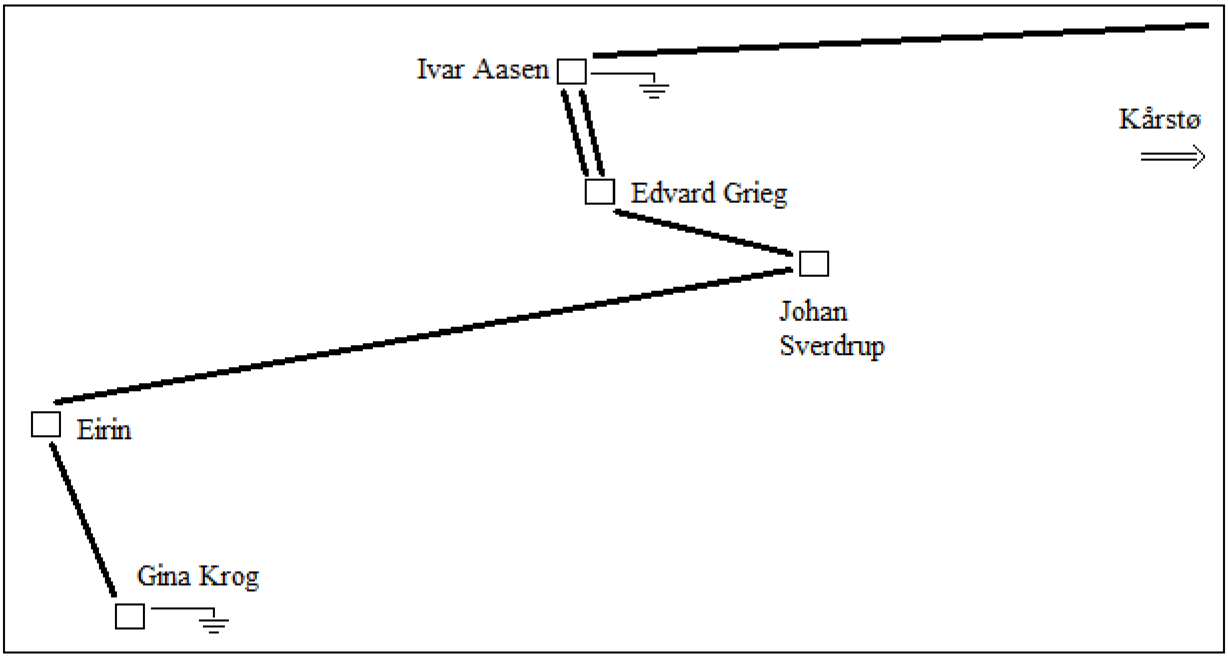


Figure 9 – Topology 1.

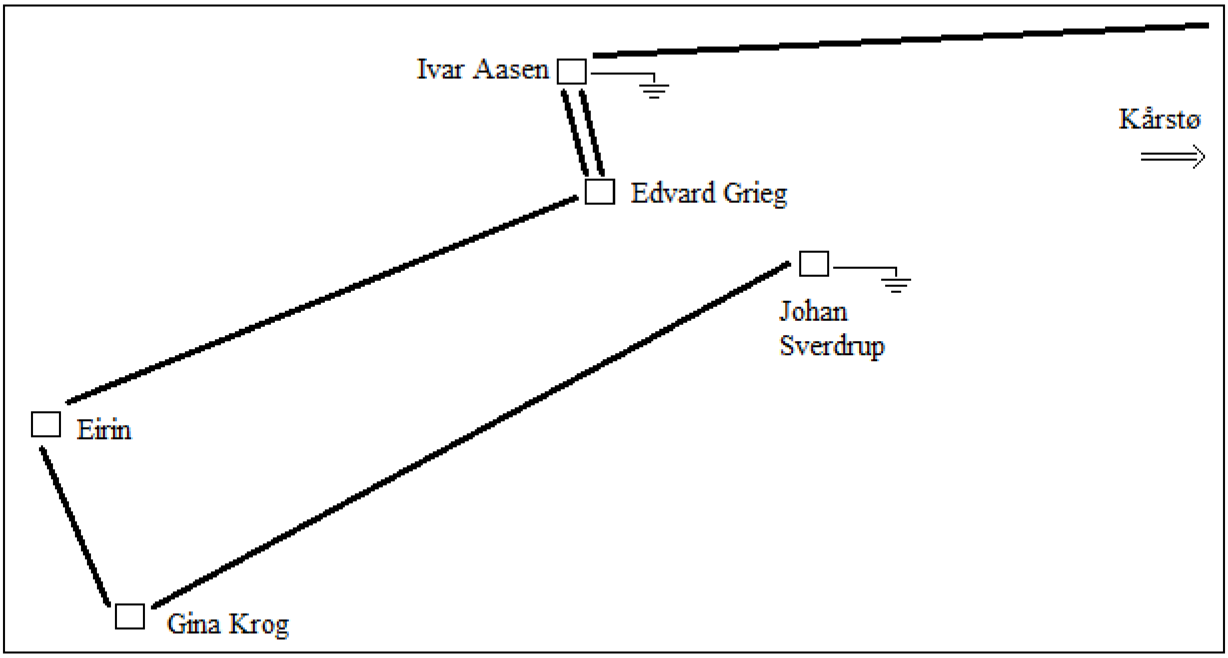


Figure 10 – Topology 2.

Although Topology 1 can be built with shorter total cable length, this advantage will be negated later when completing the second transmission cable (Step 4).

The Johan Sverdrup field has greater reservoirs than Gina Krog, and is planned to be built as a cluster of platforms connected with bridges [15]. It can therefore be assumed that Johan Sverdrup will have a greater power demand and a longer life time. The cost of a stop in production will also be greater at Johan Sverdrup. For these reasons Johan Sverdrup will take precedence over Gina Krog when prioritizing which platform will be provided with the most reliable power source. Topology 2 is therefore chosen as the preferred solution.

The two platforms not fitted with electrode arrays are required have enough generating capacity to operate independently in case of cable faults between platforms. Topology 2 therefore will save on investments, as Gina Krog is expected to require less generating capacity than Johan Sverdrup would require with Topology 1. Since Gina Krog is built with sufficient generating capacity for stand-alone operation, it can start production before Step 3 is completed.

In the event that power from shore is unavailable, the four platforms will form a network using both off-shore electrode arrays. The network will be isolated from shore and the transmission cables. In this mode the platforms will share generating capacity, and the total install capacity on Utsira High will be determined by this operation mode. Johan Sverdrup may be required to install some generator capacity beyond emergency power. Note that once shore power again becomes available, the reconnection procedure can be problematic. The shore cable is to be reintroduced to the circuit without disrupting the current in the distribution cables. To gradually increase the current in the transmission cable, the network must be connected as a meshed DC network by utilizing all three electrode arrays simultaneously.

Topology 2 does suffer a disadvantage in terms of reliability. Before Step 4 is completed, Johan Sverdrup is vulnerable to faults on distribution cables. This would render Johan Sverdrup isolated to run on on-board generators until the fault can be improved. It is therefore preferable to complete Step 4 before Johan Sverdrup is scheduled to start production. Note that after completion of Step 3 there will be two parallel cables between Edvard Grieg and Ivar Aasen to provide redundancy.

4.4.4 Step 4 – Completing shore connection

To complete the main circuit, the second transmission cable will be installed between Johan Sverdrup and Kårstø.

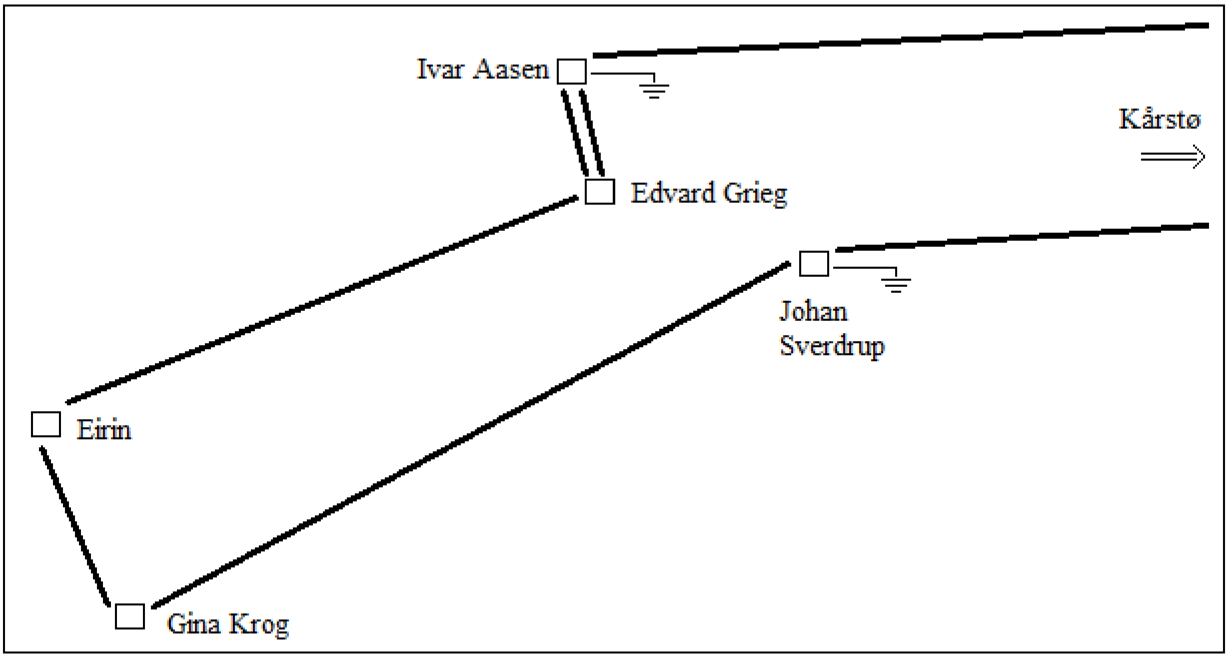


Figure 11 – Power system after completion of Step 4 in the expansion strategy.

In the completed system all platforms are supplied with power from shore. All current is conducted in cables, and the electrodes are isolated from the grid. In case of a cable fault, the electrode arrays are available as a backup.

In case a fault is detected on a transmission cable (cables extending from Kårstø), the switchgear at each end of the cable will connect the electrode array to form a conductive path in water in parallel to the faulted cable. If performed rapidly, power can continue to be supplied without interruption.

In case a fault is detected on a distribution cable (cables connecting two separate platforms), the electrodes on Johan Sverdrup and Ivar Aasen will connect, forming a conductive path between them. Johan Sverdrup and Ivar Aasen will continue to receive power from shore, while Edvard Grieg and Gina Krog will be isolated to operate at on-board generator power. The Eirin field will be left without power in this mode. Note that Edvard Grieg and Ivar Aasen have a spare cable between them to protect against such faults.

In case shore power is unavailable, or both transmission cables are faulted, the four platforms will share generator capacity between them. The transmission cables will be disconnected and the two electrode arrays at Johan Sverdrup and Ivar Aasen will be connected to complete the circuit.

In case of multiple cable faults on the system, Edvard Grieg could still supply Ivar Aasen with generator power in the same manner the platforms were operated after Step 1.

During regular operation Ivar Aasen and Johan Sverdrup observe N-1 security against cable faults, and will continue to receive uninterrupted power.

During the switching operations where electrodes are either connected or disconnected from the network, the conductive paths in water will contribute to form a meshed network on the main loop. This is to avoid changing the loop current instantaneously, while transmitting power uninterrupted. The alternative is to first de-energize the system completely, then perform switching on the electrode arrays, and finally restart the system from zero current.

4.5 Summary of solution

Step 1 – Interconnection of Edvard Grieg and Ivar Aasen

Step 2 – Power-from-shore on monopole to Ivar Aasen

Step 3 – Inclusion of Gina Krog, Eirin and Johan Sverdrup to network

Step 4 – Complete second shore cable from Johan Sverdrup to Kårstø

4.6 Analysis of solution

The expansion plan can be halted after Step 1 or after Step 2, and still be a useful installation for the remainder of the lifetime of the fields. The system will be over dimensioned in terms of current carrying capacity and will have excessive transmission losses, but the rated system current can be by increasing the number of stacked sub-modules given this investment is profitable over the expected installation life time.

Only one redundant cable was installed during the expansion, and it serves the purpose as a spare in the completed system. If the cables are connected in parallel during normal operation, the copper losses can be reduced. The total number of electrode arrays can be reduced from three to two, if a cable is installed between Johan Sverdrup and Ivar Aasen.

The subsea field Eirin is the only part of the installation which does not have a source of backup power. Because of the risk of fault on the distribution cables, it could be argued that it would be better to supply Eirin with AC cables from Gina Krog instead of including the site as a part of the MSDC main loop.

5 Simulations

5.1 Description of simulation model

The simulation model is created in Simulink using the SimPowerSystems library for electrical components. Simulink is a software block diagram simulation environment with fixed-step and variable-step solvers of differential equations. Simulink is integrated with the MATLAB computing environment.

The simulation model is built as an average model, except for Scenarios 6 and 7 where a switched model is applied.

The source converter is modeled as a controlled voltage source, operating to keep loop current at a reference value. Upstream components, such as grid, transformers and rectifiers, are not modeled. As discussed in [1] the source converter can be implemented as multiple topologies. The simulation employs an ideal converter model and emphasizes the effects of the control strategy.

The transmission lines are modeled as multiple pi-sections. At the terminations of each line there must be included a small resistor, since the shunt elements of pi-sections cannot be connected in parallel with voltage sources.

At the load side of the circuit, several stacked sub-modules are represented in the simulation model as an aggregate module, referred to as a (load) converter. With the exception of the switched converter module, each converter represents 20 stacked sub-modules, and contains a single capacitor element representing the combined capacitors in the stack. In the following simulated scenarios the loads in the MSDC system are represented with two such converters. The converters are of identical rating and have identical control systems. In each scenario, one converter will either be subjected to a disturbance in load or be given a command to trip. The second converter will remain on-line during the event, and will attempt to continue transmitting power. The converter serves the purpose of showing how a disturbance in one part of the system can affect other components.

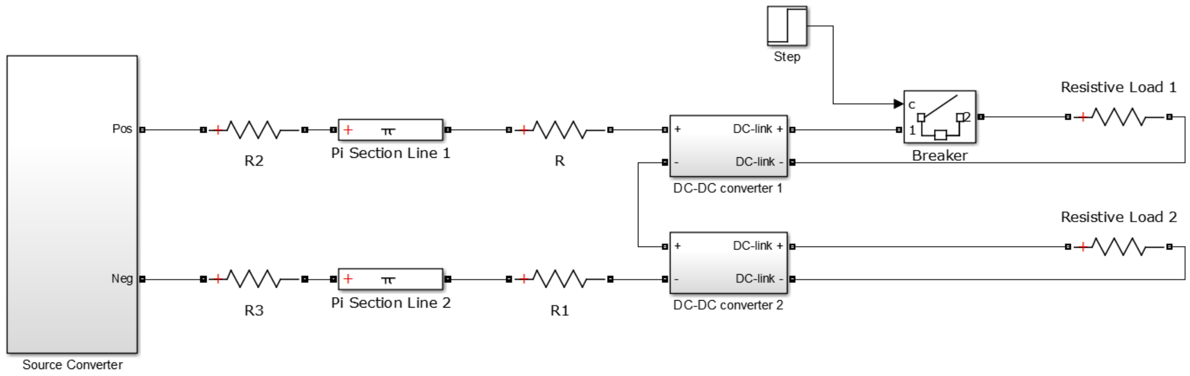


Figure 12 – The complete simulation model used in Scenario 1.

The model applies a distributed control system, where each sub-module uses only information available through internal measurements. Each converter is operated with a feedback control system with a PI regulator.

The input signals to the sub-modules are reference current/voltage and the commands to turn ON or OFF. The amount of power drawn by downstream loads is programmed to change during the simulations, which is considered a disturbance for the control systems.

5.2 Scenario 1: Load connection as step

In the initial conditions two converters are energized; one converter is operating at no load while the other is operating at 20 MW load. The total power demand in the system will be instantaneously doubled, as current is drawn by the load from the previously idle converter.

This scenario is considered an extreme transient in the system because it involves a large change in power over a very short time. A controlled connection of additional load would typically span over seconds, where rotating machines gradually draw increasing amount of active power. The following describes an incident where the power demand could realistically double instantaneously: Assume a platform is initially generating 50% of its power locally and receiving the remainder through power-from-shore. If the onboard generators were to trip, the full power demand would have to be supplied from shore.

Measurements presented in graphs below are taken at the converter experiencing load increase and at the source converter.

5.2.1 Capacitor charge and discharge current

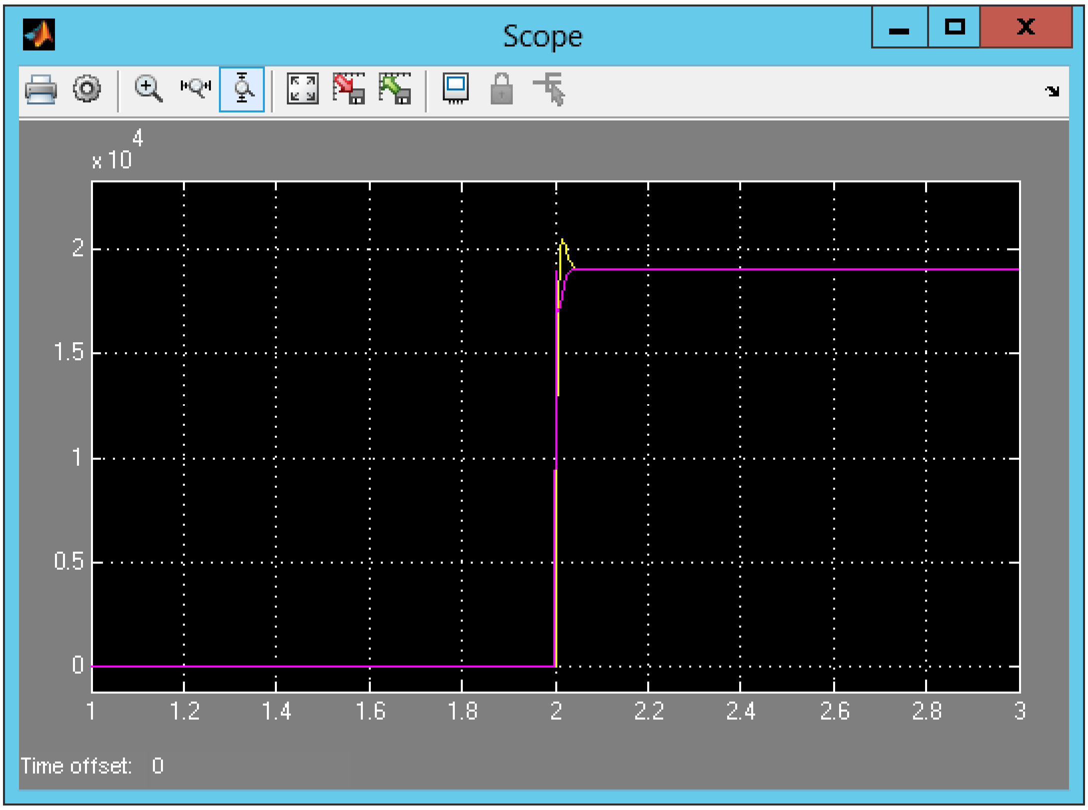


Figure 13 – Currents directed into (yellow) and out from (pink) the node at positive terminal of the capacitor.

The load is connected at t=2 seconds, and the power demand is instantaneously increased from 0 to 20 MW. The difference in currents during 2.01<t<2.04 is the response of the converter regulator to compensate for capacitor voltage dip (see below).

5.2.2 Capacitor voltage

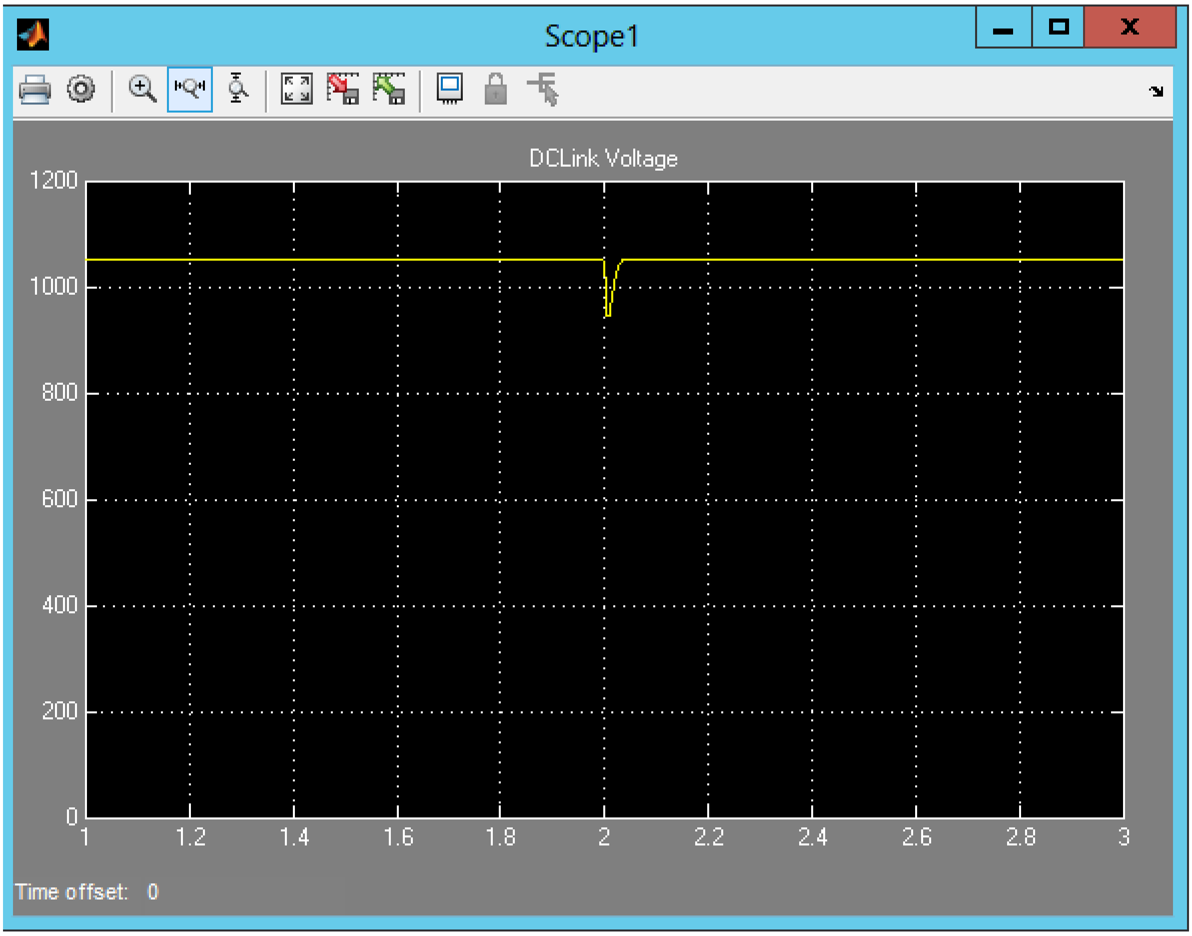


Figure 14 – Voltage over the capacitor in load converter.

The capacitor experiences a voltage dip at the time of load connection. The regulator increases the duty cycle of the DC-DC chopper until voltage is restored to reference value.

The inverter will observe the same voltage dip. VFDs are vulnerable to deviations in voltage, and if the voltage becomes too low this can result in a trip of the inverter. Such a trip will cause another change in the total power demand, this time to a lower level, and cause further transients in the system.

5.2.3 Converter voltage over loop

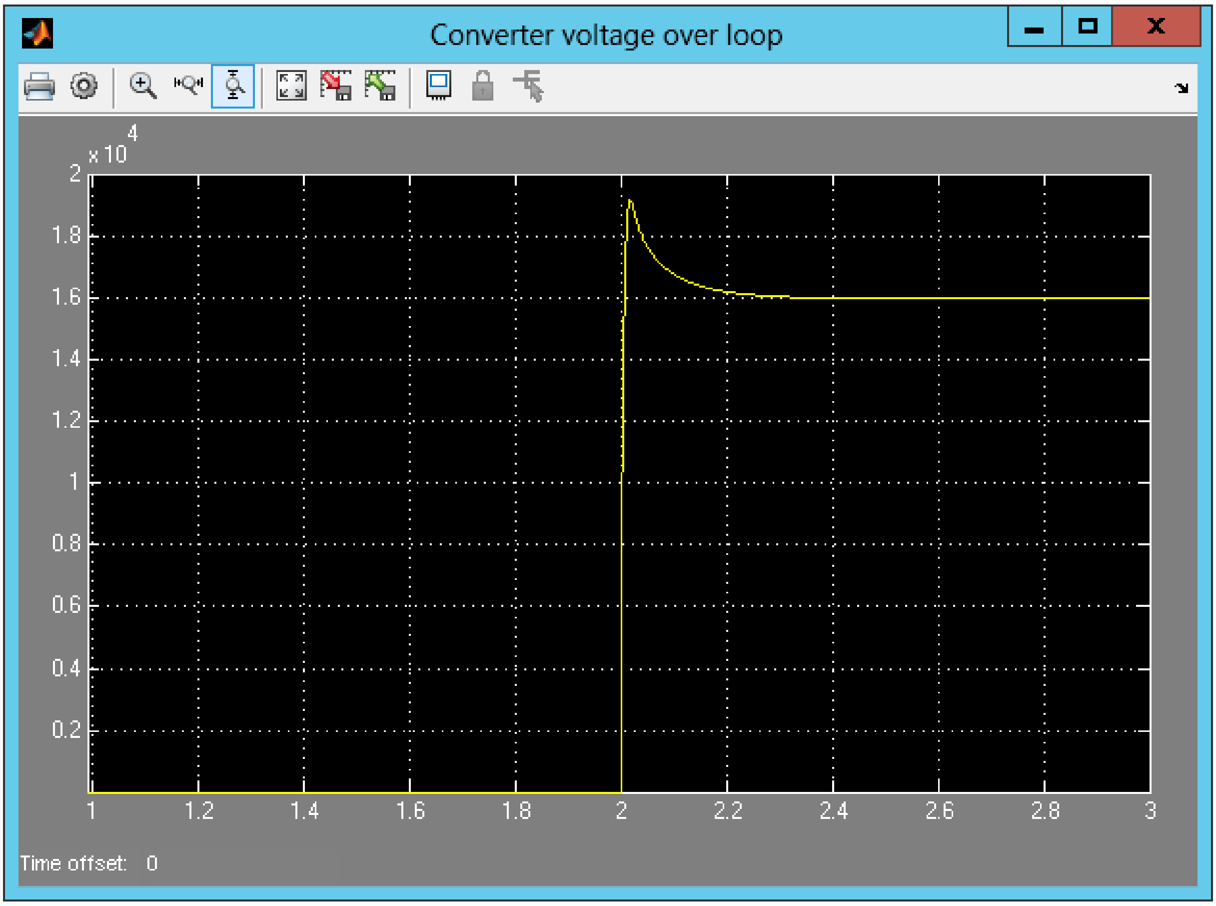


Figure 15 – Apparent voltage applied by the load converter to the main current loop.

The voltage overshoot is 3 kV or 19% above the new steady state value.

5.2.4 Loop current measured at load converter

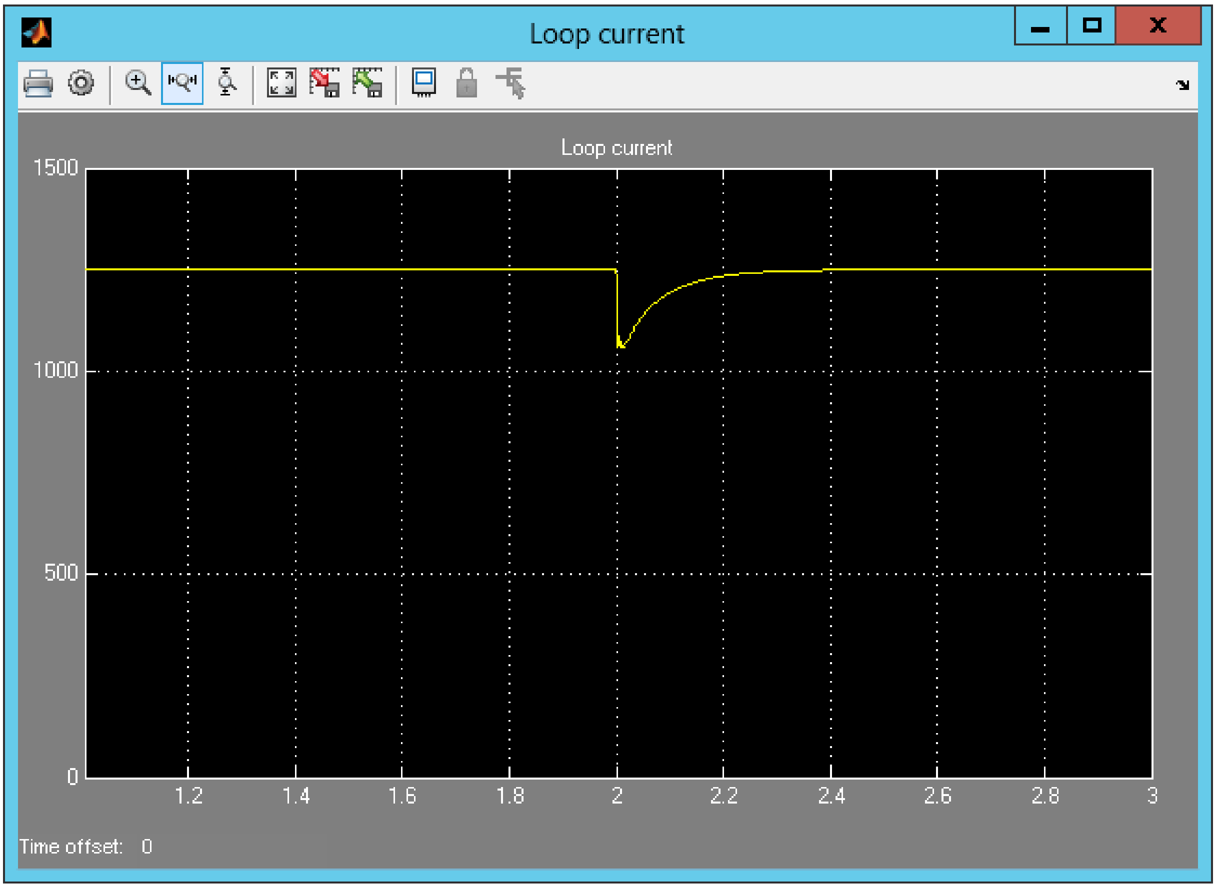
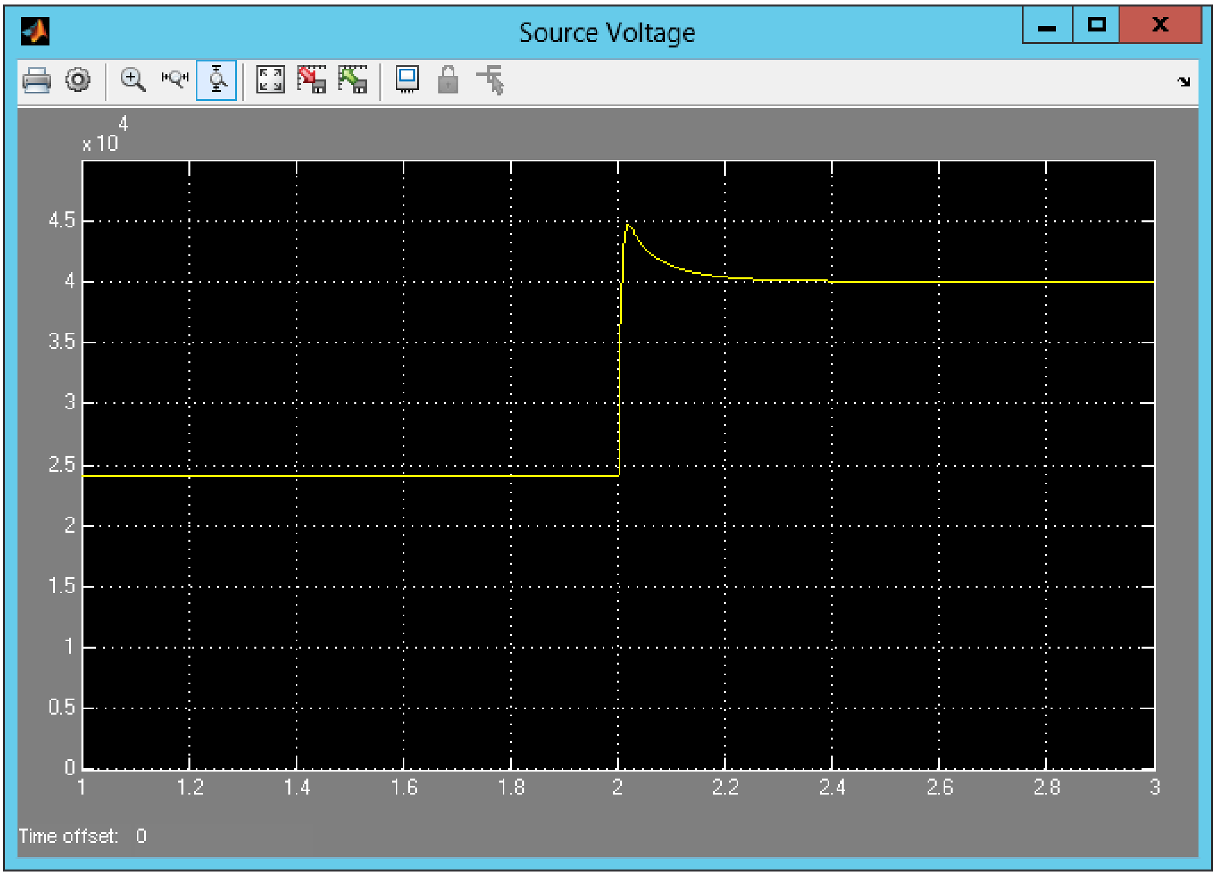


Figure 16 – Loop current measured at load converter.

The current dip is significant, and will cause other converters in the system to increase their duty cycle to maintain constant power flow. This regulation action will increase all converter voltages temporarily and will be observed by the source converter (see below).

The new equilibrium has no steady state error in current value.

5.2.5 Source voltage



Time offset: 0

Figure 17 – Voltage measured over source converter.

Steady state voltages before and after the transient can be decomposed as the following:

Before: V_converter + V_cable = 16 + 8 kV = 24 kV

After: 2*V_converter + V_cable = 2*16 + 8 kV = 40 kV

The total system voltage changes very rapidly at t=2 seconds. The transient has a voltage overshoot at source converter of 5 kV, or almost the sum of simultaneous overshoots at the two load converters. The reduction in loop current contributes to a small temporary reduction in voltage drop over the transmission cables, reducing the total peak voltage.

The source voltage and the loop current are two strongly correlated values, and the time constants of convergence to steady state value are almost identical in the plots of the two variables. The convergence time can probably be improved by modifying the control system.

The resulting loop current dip is of significant amplitude, but all converters and control systems ride through the transient, continue to supply all loads, and settle to a new steady state equilibrium.

5.3 Scenario 2: Load connection as ramp

Scenario 2 is derived from Scenario 1, but gradually increases the load power over time. In the initial conditions, Converter 1 is energized but transmitting no power to the downstream loads. During the transient, the power drawn from Converter 1 increases linearly to 20 MW. The total power delivered by the system is doubled over 0.5 seconds.

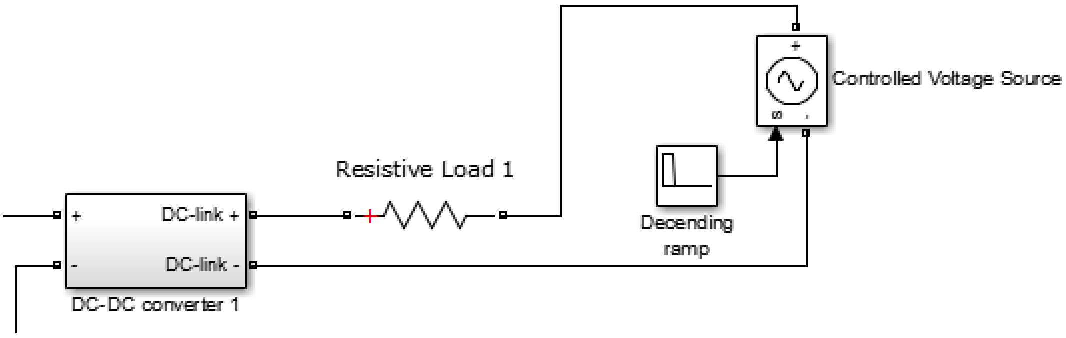


Figure 18 – Converter undergoing change in load power in Scenario 2. The voltage over resistor (and active load power) is initially zero, then increases over 0.5 seconds to the full capacitor voltage.

5.3.1 Capacitor charge and discharge current

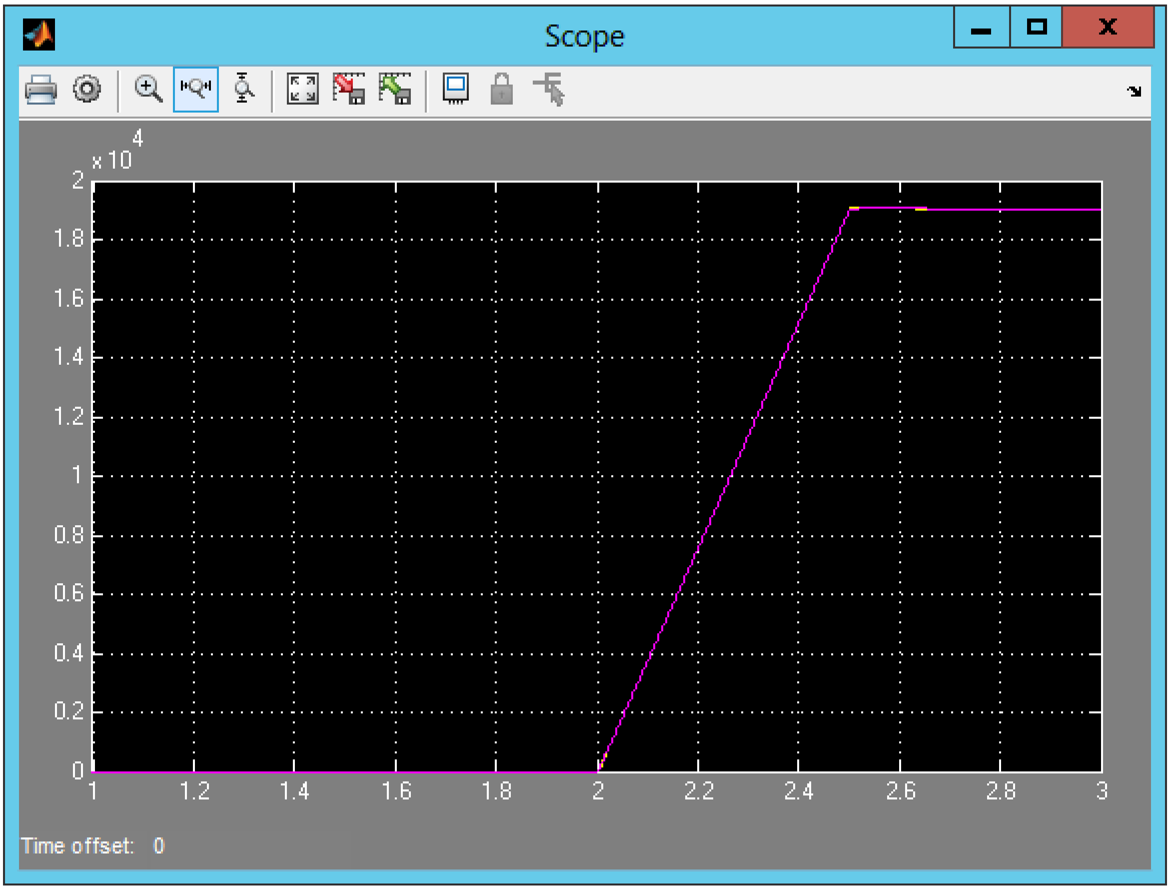


Figure 19 – Currents directed into (yellow) and out from (pink) the node at positive terminal of the capacitor.

The values of the two currents are nearly identical at any given time. This result implies that there is very little change in capacitor voltage.

5.3.2 Capacitor voltage

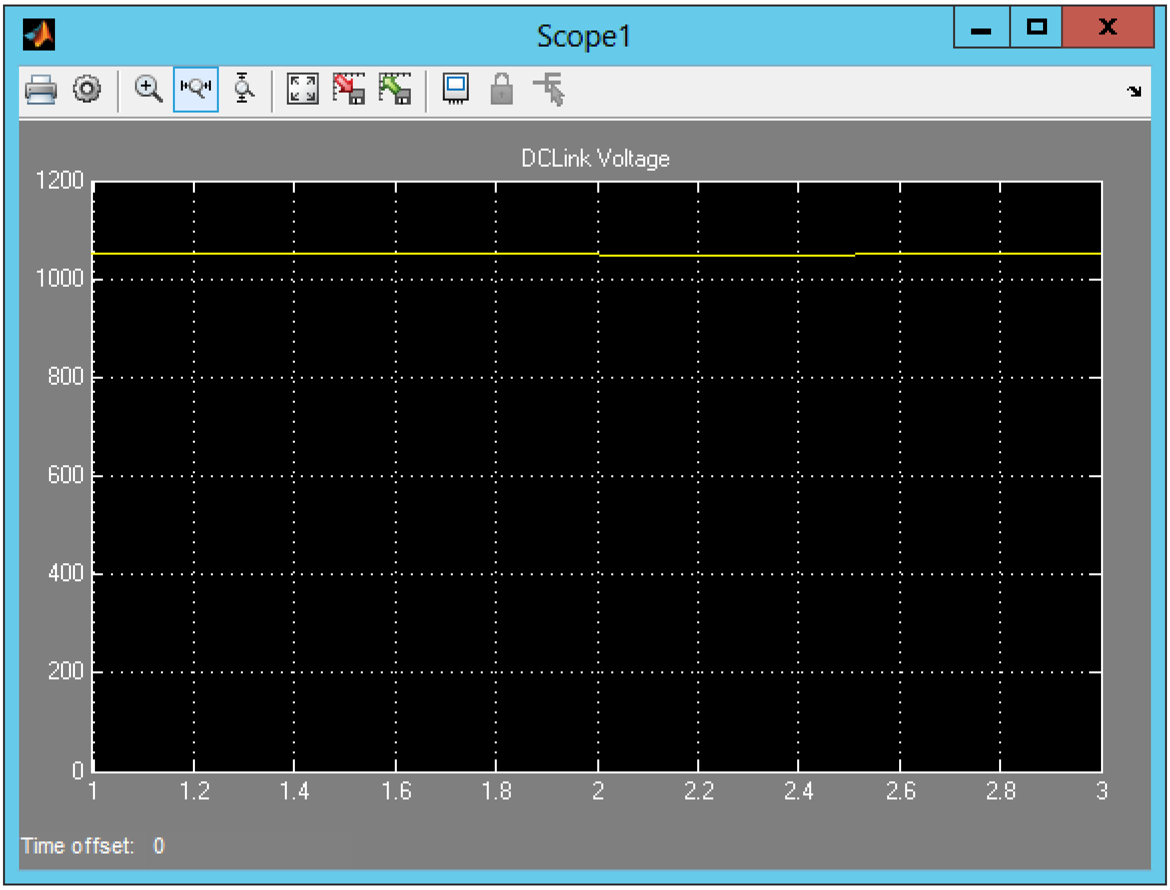


Figure 20 – Voltage over the capacitor in load converter.

The voltage drop at capacitor is very small, and should not affect the performance of the downstream inverter.

A small offset in voltage during ramping is necessary for the controller to continue to increase the duty cycle at the DC-DC chopper. The voltage offset disappears as soon as the load power is constant at t=2.5 seconds.

5.3.3 Converter voltage over loop

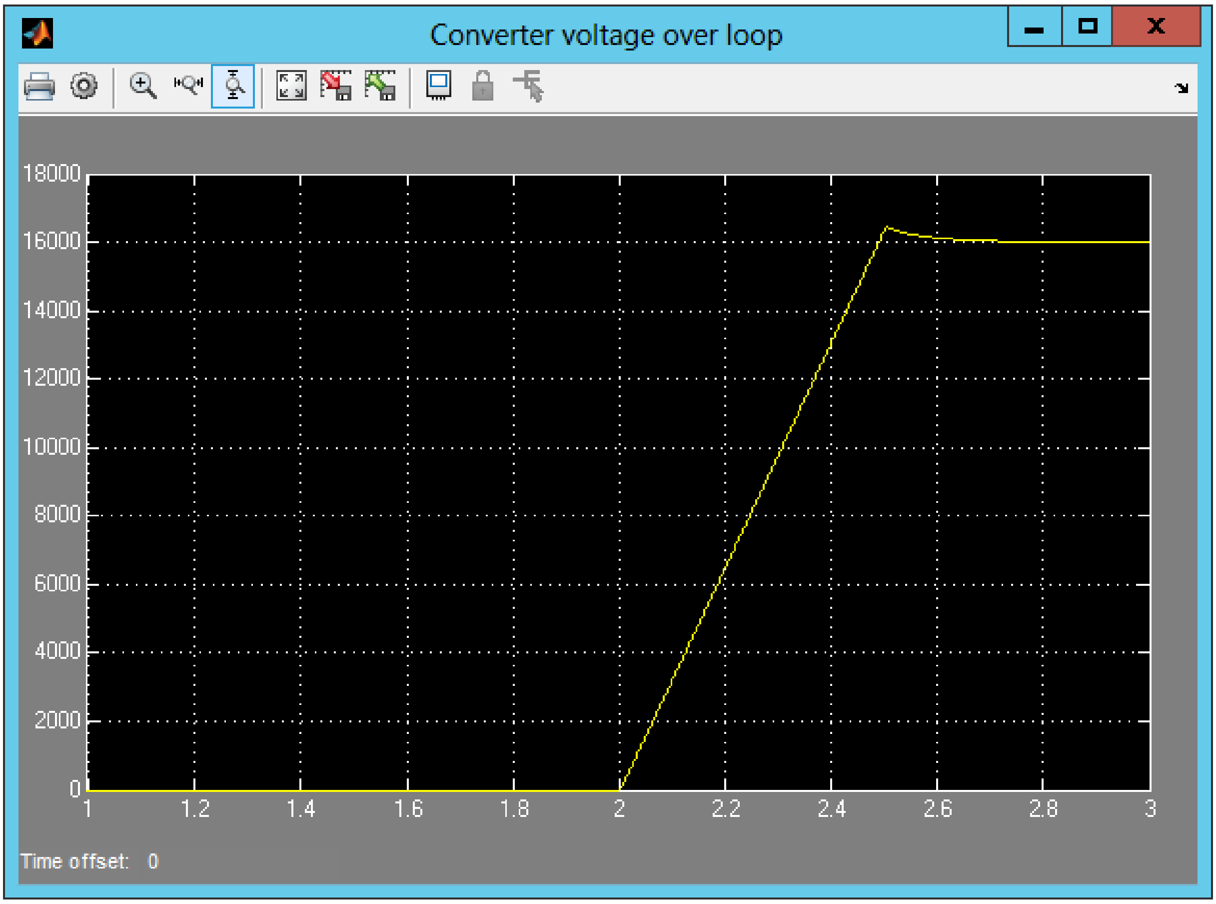


Figure 21 – Apparent voltage applied by the load converter to the main current loop.

Load power is modeled to increase linearly, thus the voltage increases linearly. Voltage overshoot is 0.5 kV or 3 % above new steady state value.

5.3.4 Loop current measured at load converter

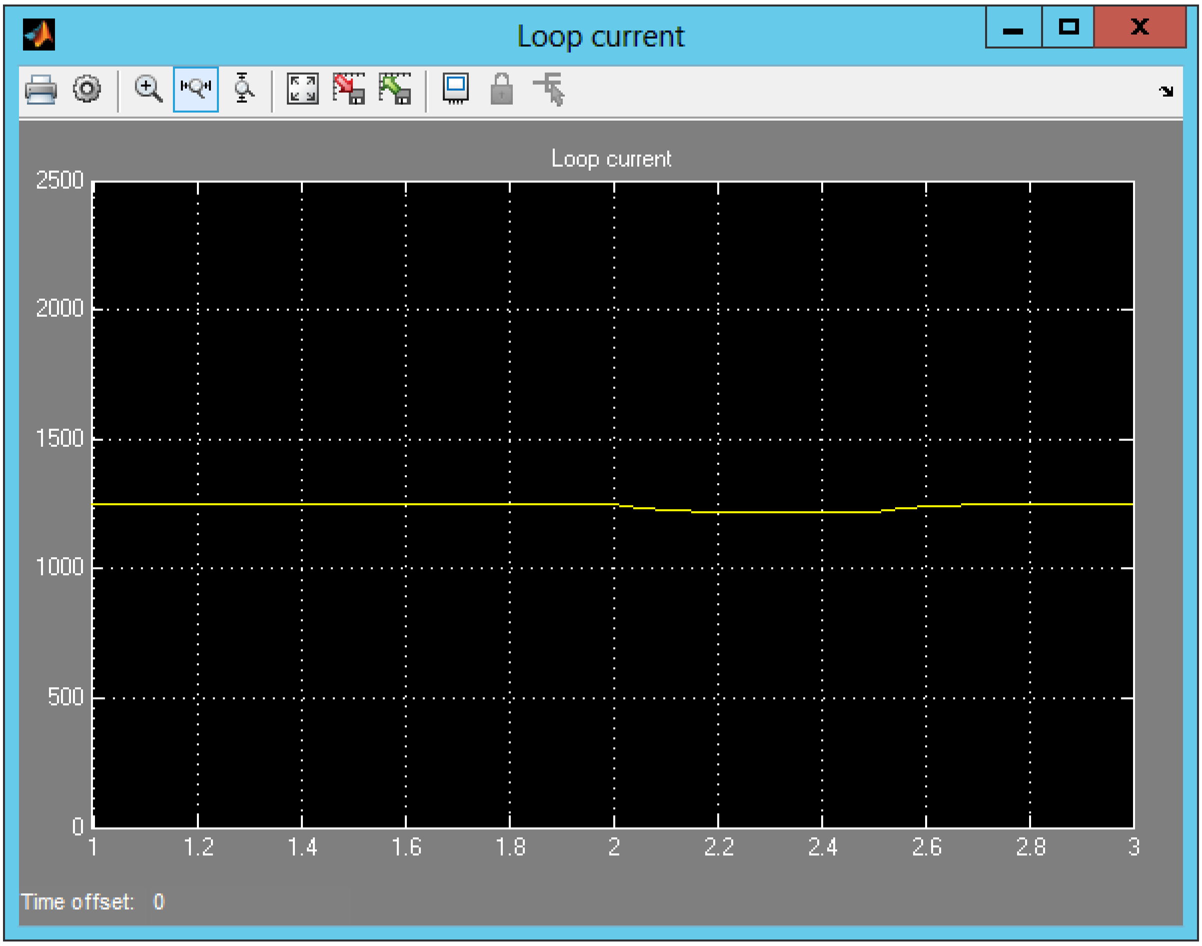


Figure 22 – Loop current measured at load converter.

The main loop undergoes a current drop for the duration of the fault. It takes additional time after the load ramping is complete before the rated current is restored. Compared with Scenario 1, where there was a step change in load, the current drop is smaller both in amplitude and maximum d/dt.

An improved source control system could possibly eliminate the offset during ramping and make the current converge more rapidly after a disturbance.

5.3.5 Source voltage

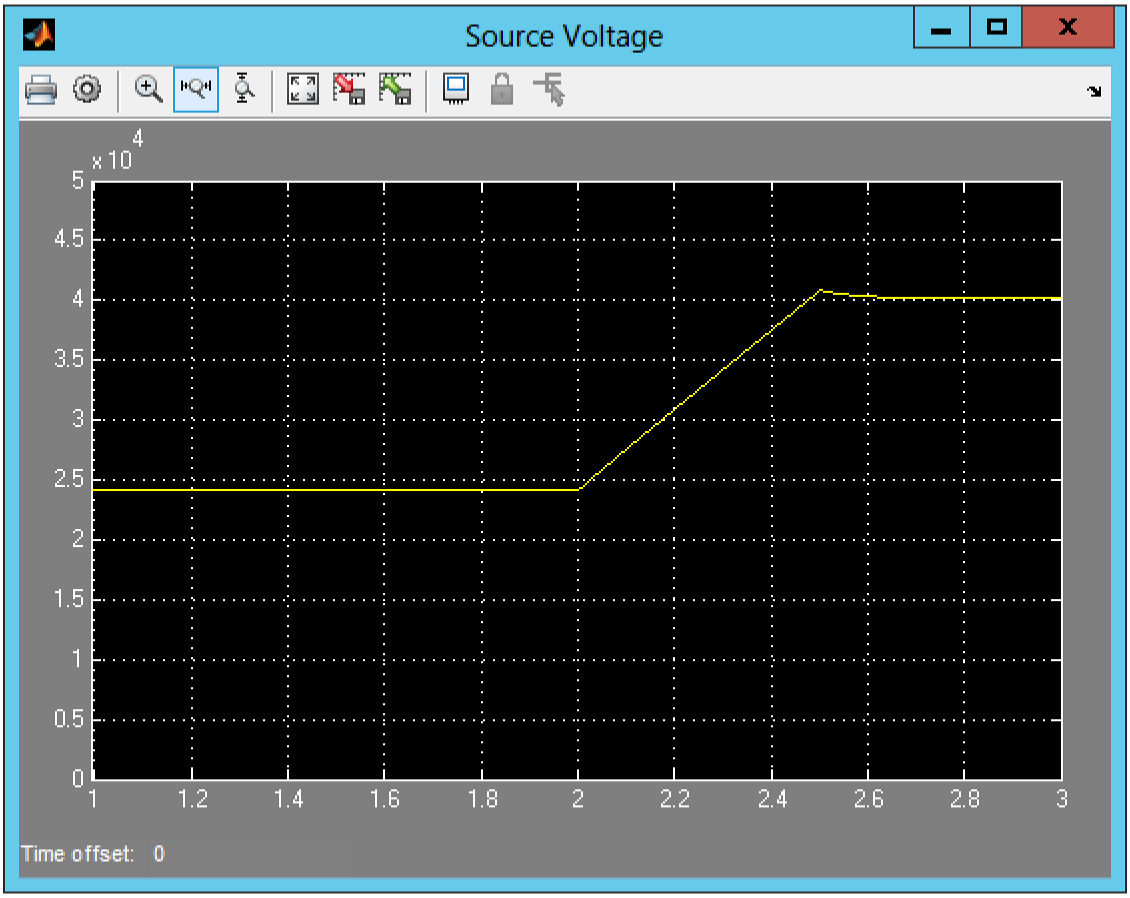


Figure 23 – Voltage measured over source converter.

The system stabilizes at a new steady state after the load connection. The steady state voltage levels, and thus the power flow solution, are identical to Scenario 1.

The voltage overshoot at source is 0.7 kV. At both the load converter and the source converters, the voltage overshoot is far smaller than in Scenario 1. Unlike in Scenario 1, the load converter that does not experience a change in load power will apply a far smaller over-voltage on the loop. The small over-voltage is inverse proportional to the current value on the main loop. The two load converters will also reach their respective peak voltage at different times (50 ms apart), instead of simultaneously as in Scenario 1.

Despite the additional time before the system stabilizes, this form of controlled ramp change of load voltages is preferable to the step response because of smoother transients. Consequently, the ramp method involves less chance of causing equipment to trip, imposes less strain on equipment, and reduces the risk of isolation failure from over voltages.

5.4 Scenario 3: Load shedding

The initial conditions in this event involve both load converters operating at rated power. At t=2 seconds all load downstream of Converter 1 is abruptly disconnected. The total system power is instantaneously reduced to half the initial condition.

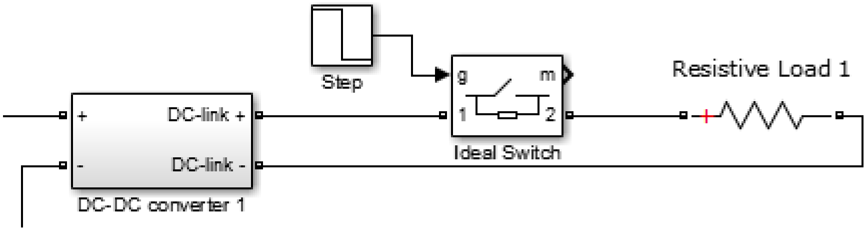


Figure 24 – Converter undergoing change in load power in Scenario 3.

5.4.1 Capacitor charge and discharge current

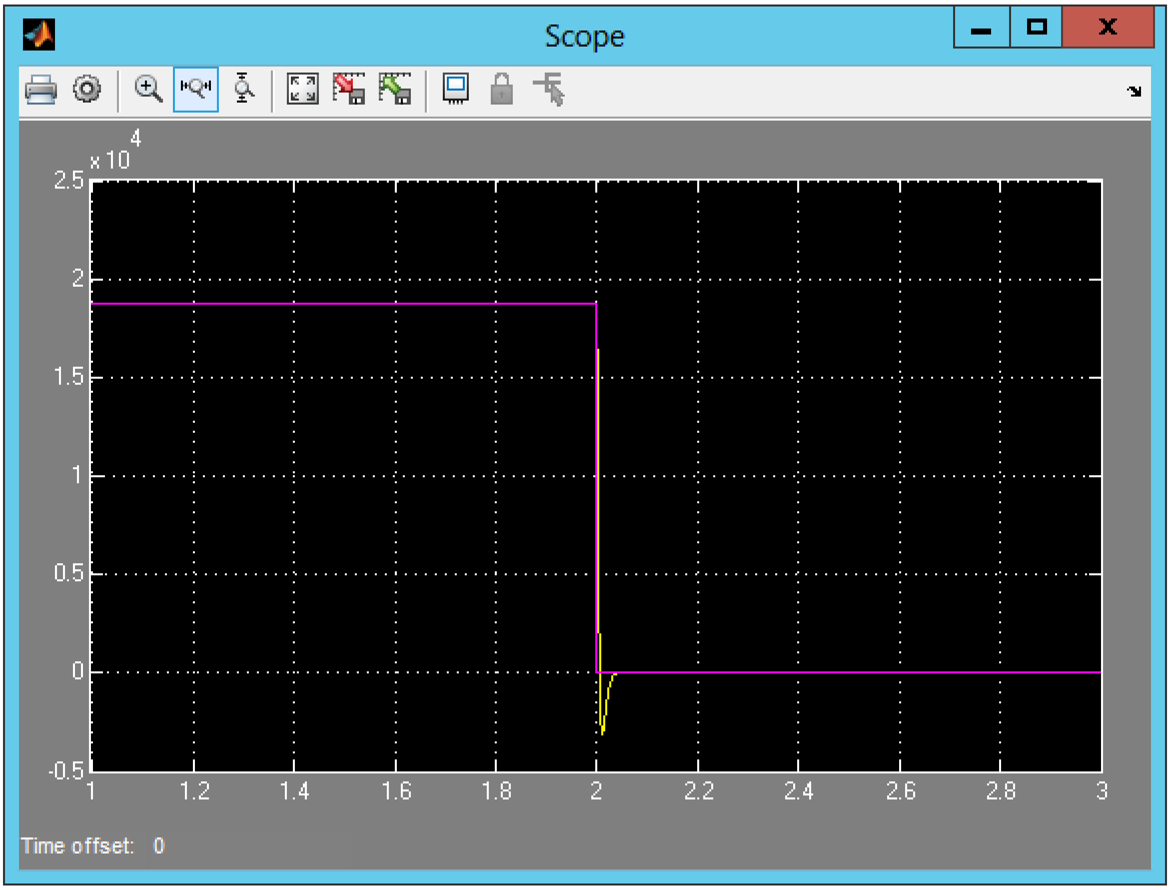


Figure 25 – Currents directed into (yellow) and out from (pink) the node at positive terminal of the capacitor.

The load current changes rapidly to zero. The incoming capacitor current (yellow) is negative for a short duration, implying that the capacitor is discharging an overvoltage through the DC-DC chopper.

5.4.2 Capacitor voltage

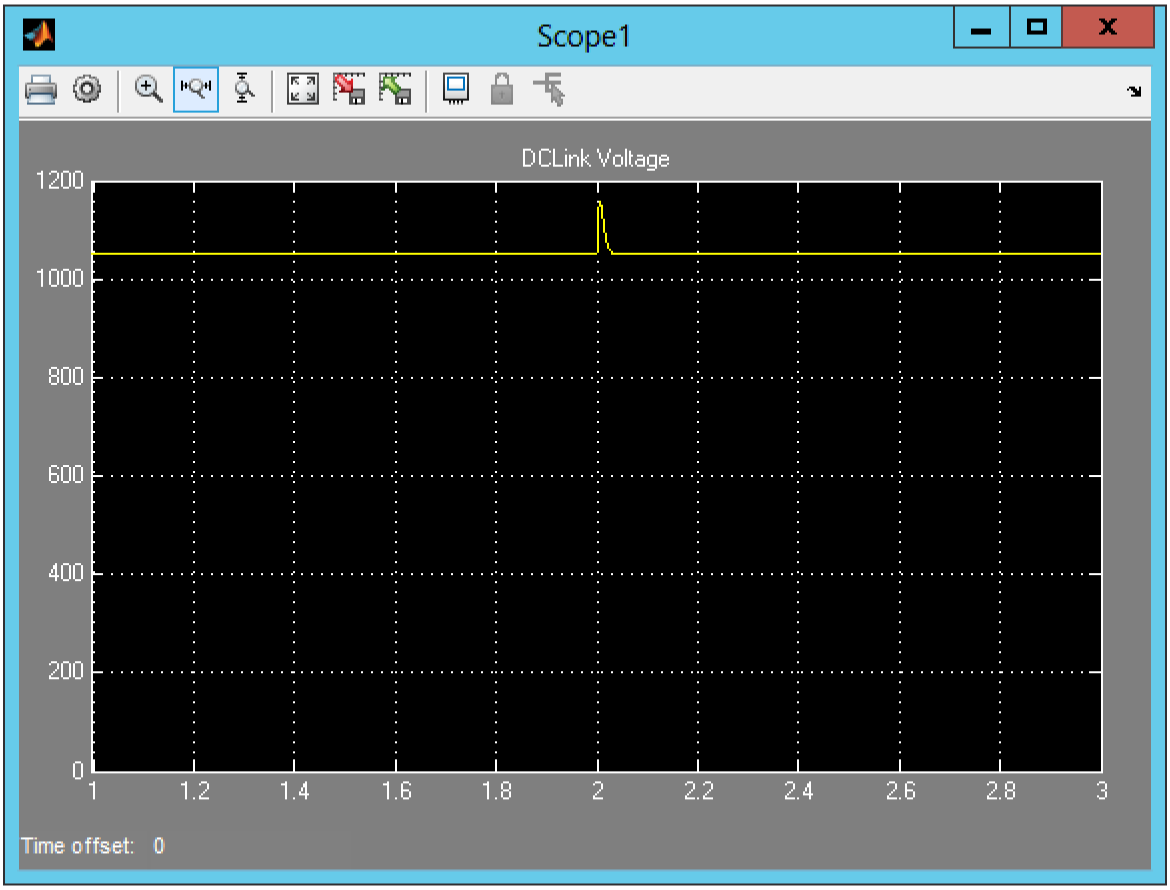


Figure 26 – Voltage over the capacitor in load converter.

The capacitor voltage peaks before the converter control system reacts to restore the voltage.

The converter remains energized after the load disconnects.

5.4.3 Converter voltage over loop

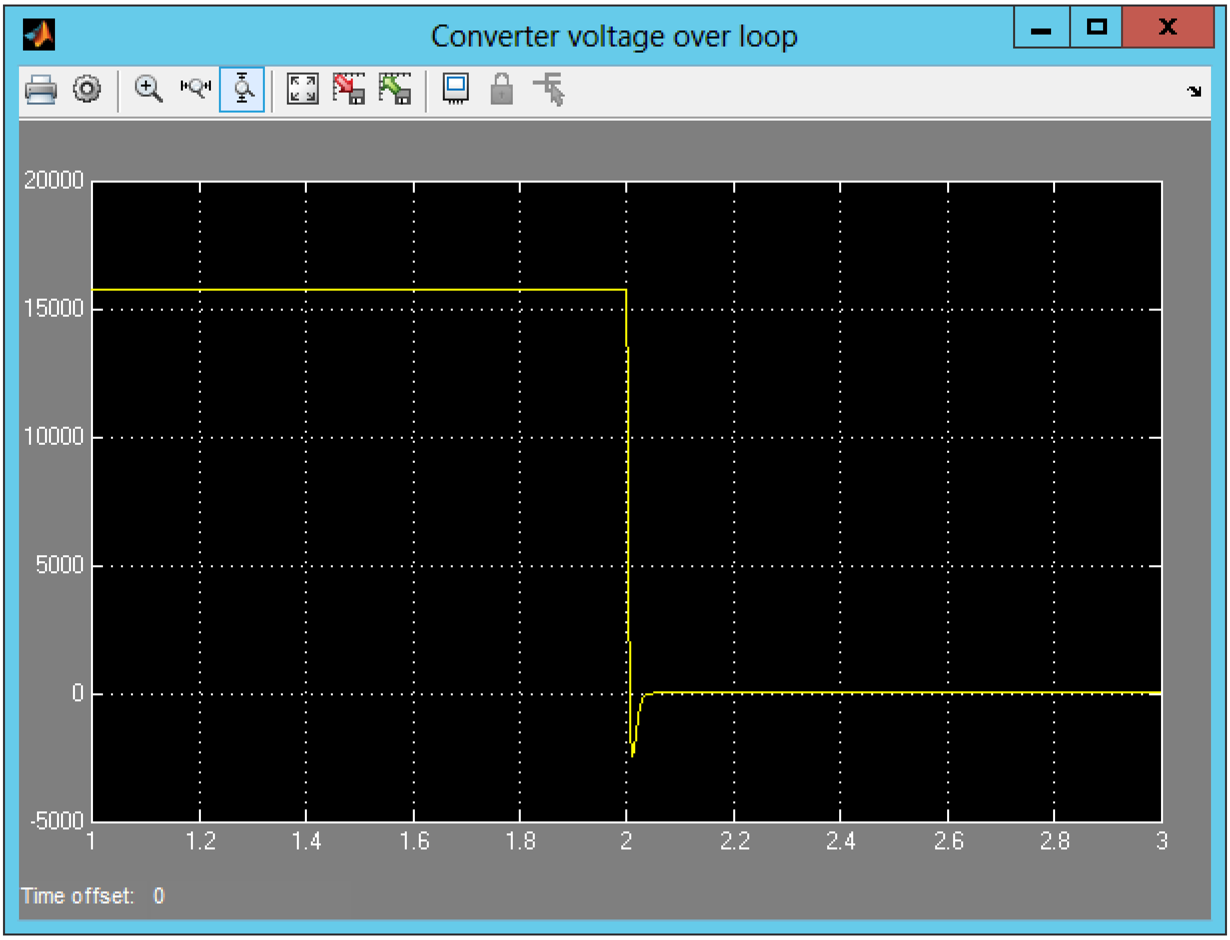


Figure 27 – Apparent voltage applied by the load converter to the main current loop.

The short period of negative voltage is indicative that the capacitor is discharged through the DC-DC chopper and feeding power back to the main loop. This process employs a switching state where both IGBTs of a sub-module are conducting simultaneously.

5.4.4 Loop Current measured at load converter

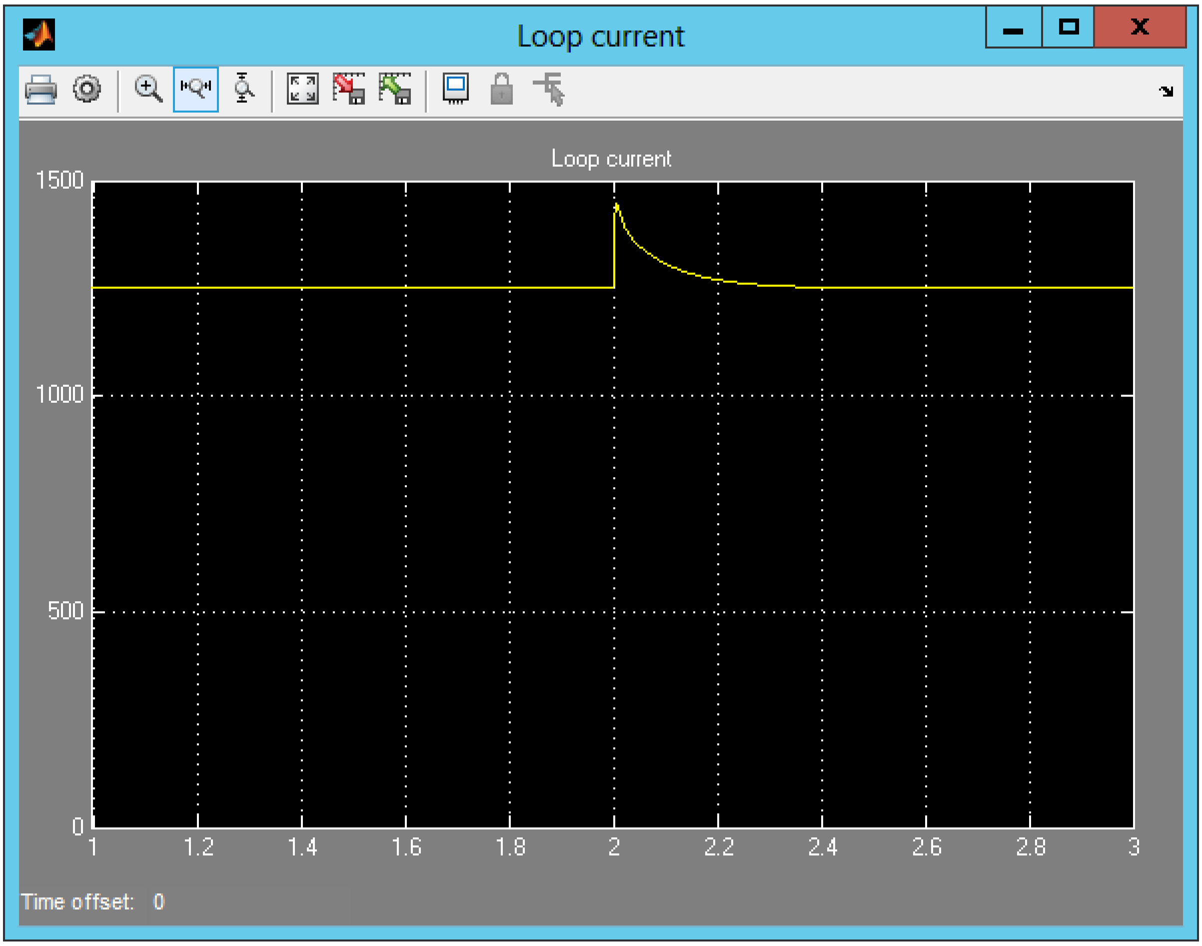


Figure 28 – Loop current measured at load converter.

There occurs a current peak with a relatively long decay time. The amplitude and decay time of the current peak is comparable to Scenario 1.

5.4.5 Source voltage

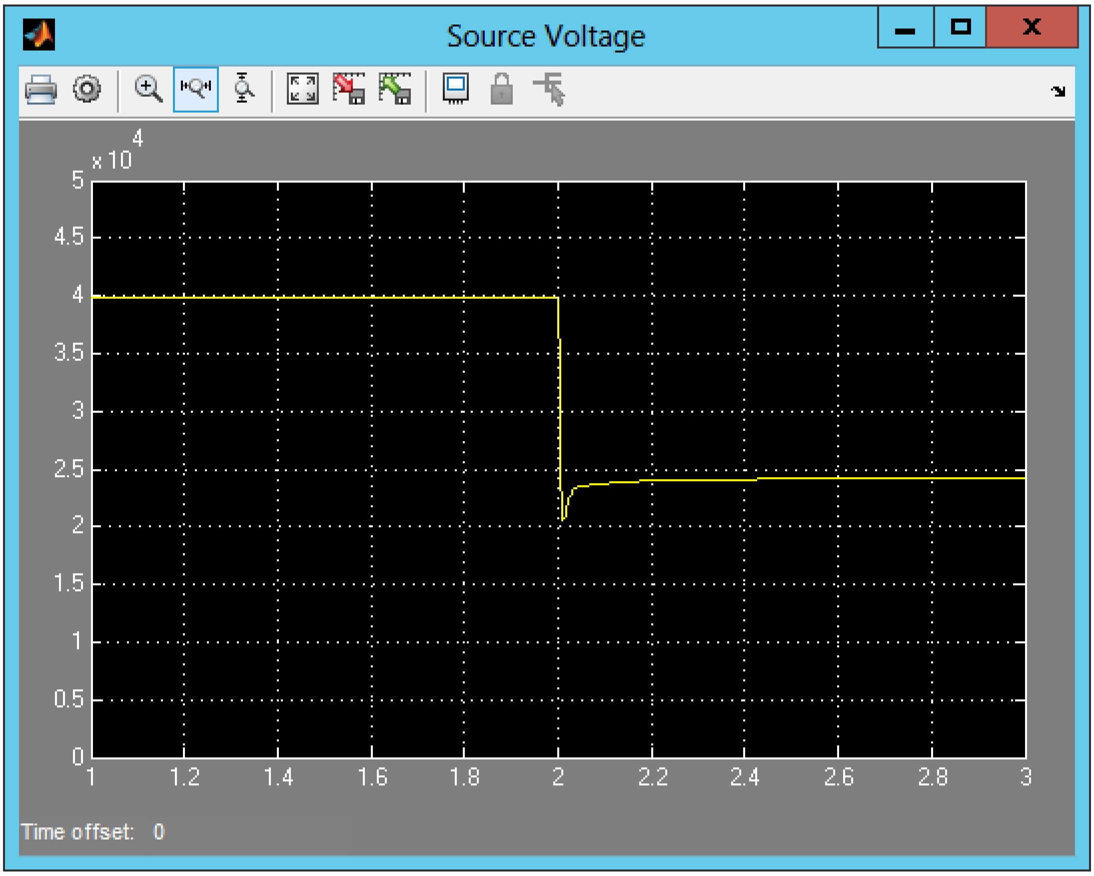


Figure 29 – Voltage measured over source converter.

After the load reduction all converters remain energized and ready for the load power to resume at any given moment. Note that no external commands were given to any converters during the simulation. The response is attributed solely to the feedback control systems.

5.5 Scenario 4: Trip with bypass switch

The initial conditions are identical to Scenario3, with two converters operating at rated power. At t=2 seconds one converter will simulate the detection of an internal fault and trip. The converter will disconnect and isolate from the main network. The total system power will be reduced to half.

All plots and measurements are taken from the viewpoint of the tripped converter.

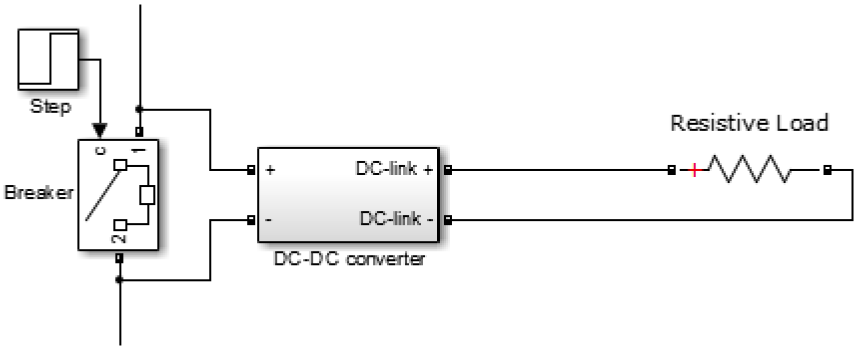


Figure 30 – Converter undergoing a trip in Scenario 4 and 5.

5.5.1 Converter voltage over loop

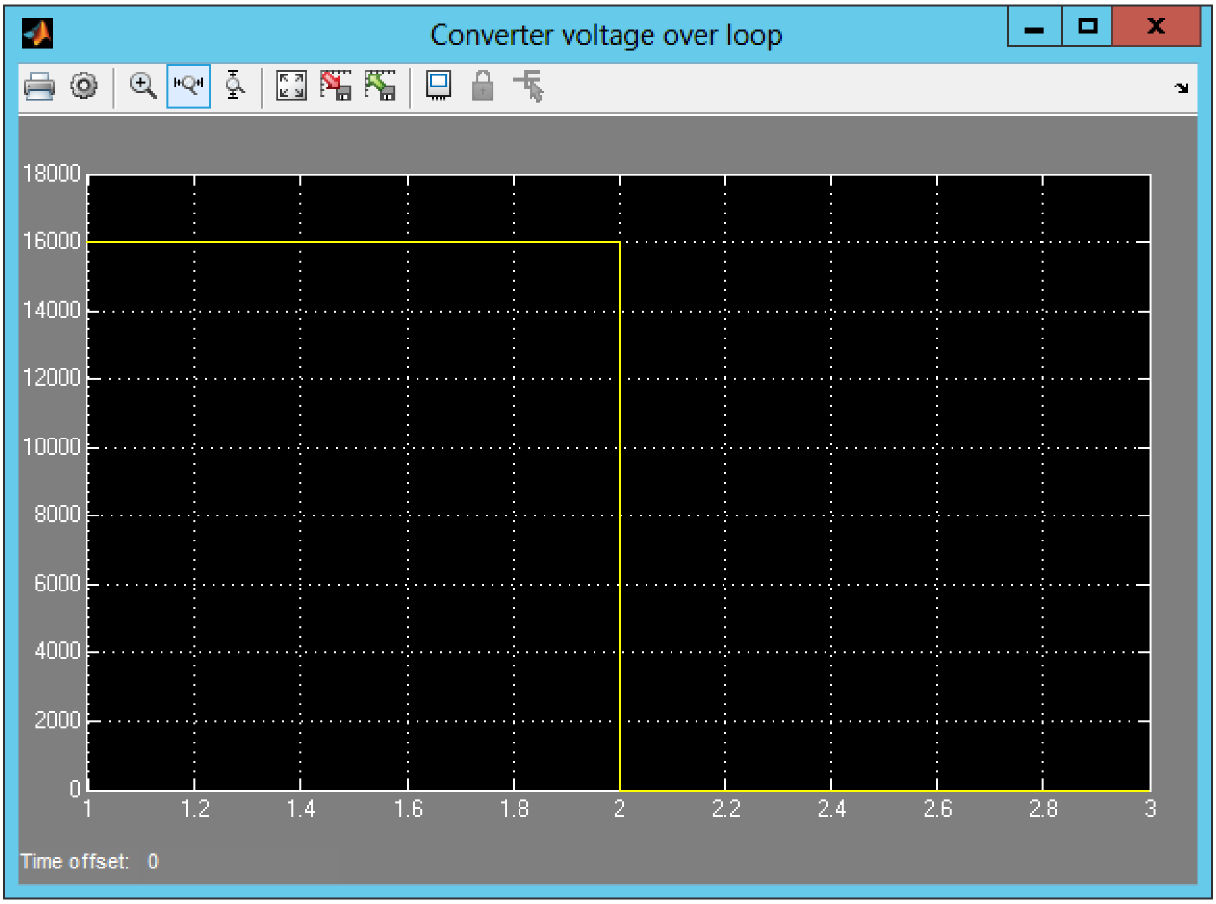


Figure 31 – Apparent voltage applied by the load converter to the main current loop.

After the trip, power transmitted between the main loop and converter is zero. The reduction in power is instantaneous. By comparison, the load shedding in Scenario 3 caused the converter to feed power back to the loop after the load reduction.

5.5.2 Capacitor voltage

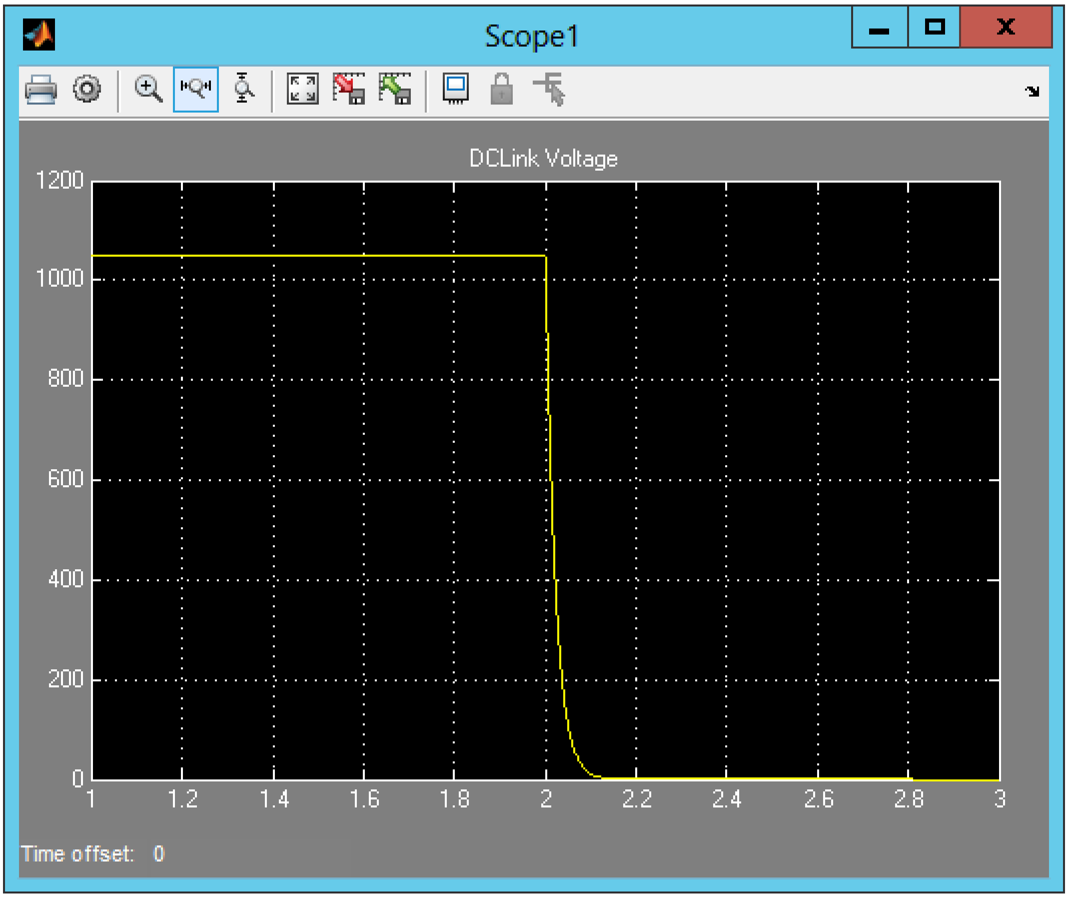


Figure 32 – Voltage over the capacitor in load converter.

The currents drawn by downstream loads will discharge the capacitor. No additional power is transferred from the loop to the capacitor after t=2 seconds.

A different implementation of the trip procedure is described in [1]. After the bypass switch has shorted the primary converter terminals, the IGBTs in DC-DC chopper will start conducting and thereby shorting the terminals of the capacitor. The capacitor will rapidly discharge and dissipate heat over the IGBTs and bypass switches.

5.5.3 Loop current measured at load converter

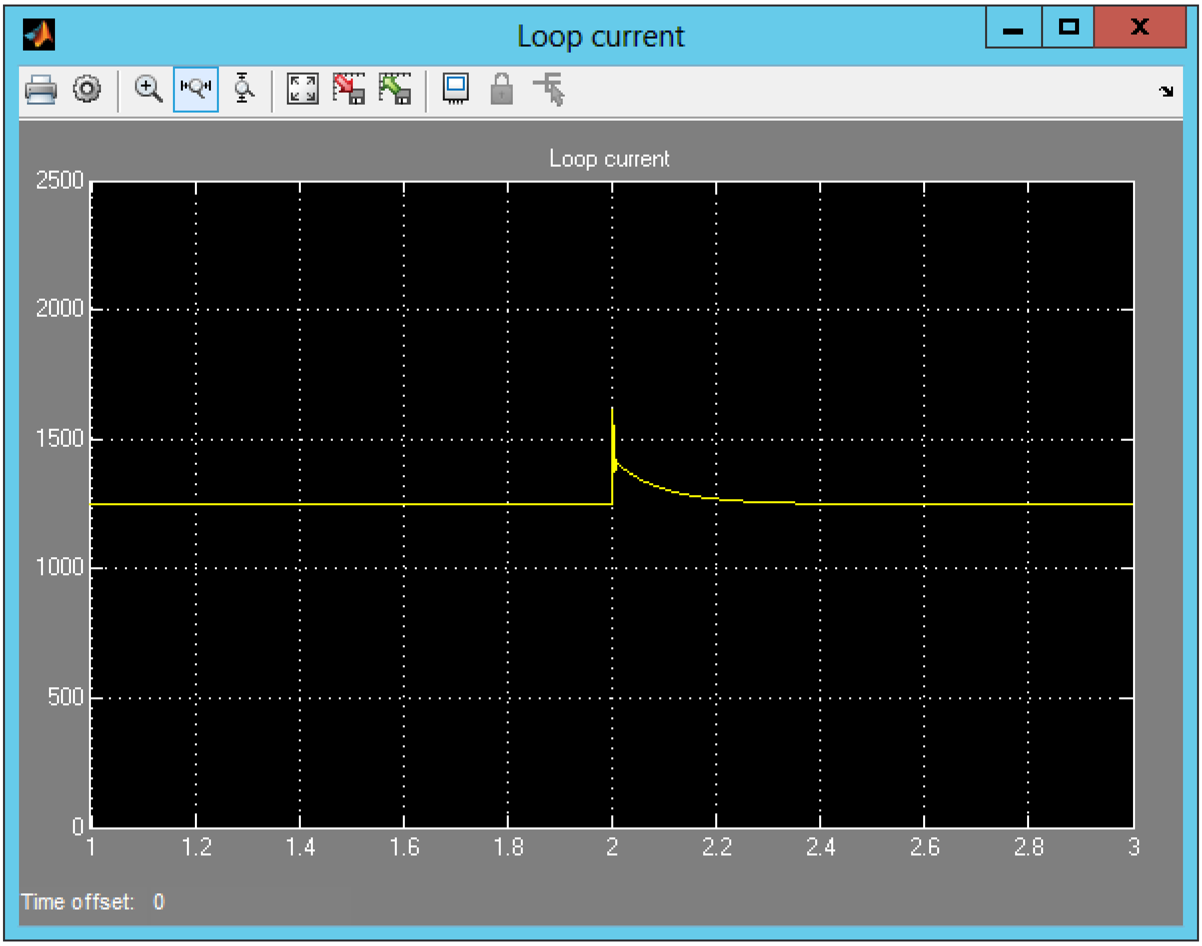


Figure 33 – Loop current measured at load converter.

The initial peak value is dependent on the modeling of transmission cables with pi sections. The actual peak value cannot be accurately estimated because of the limitations in the cable model.

The time constant of convergence is comparable to Scenarios 1 and 3.

5.5.4 Loop current measured at source converter

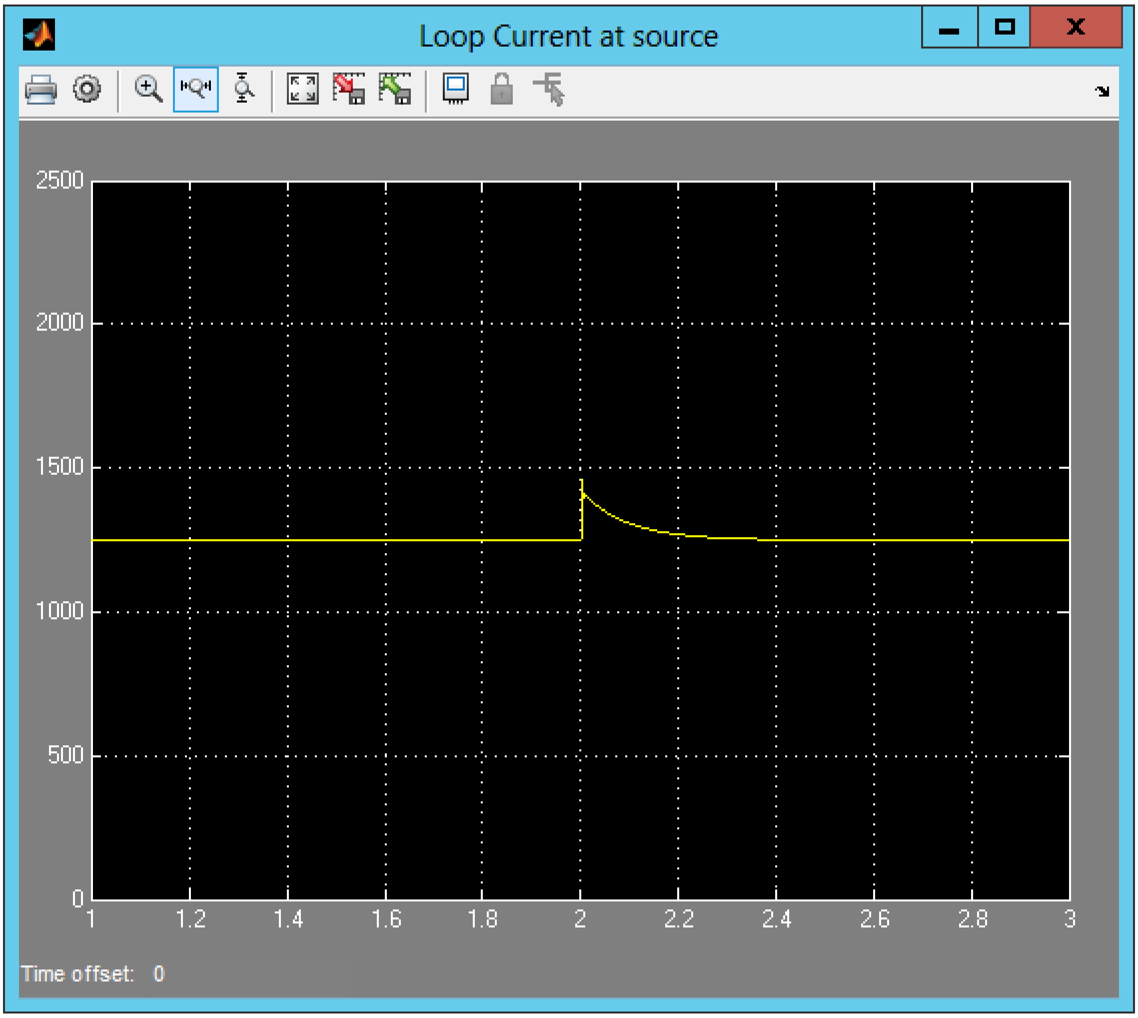


Figure 34 – Loop current measured at source converter.

The peak value that can be observed at load converters is reduced over the cable.

5.6 Scenario 5: Ride through of converter adjacent to tripped converter

This events modeled in Scenario 5 are identical to Scenario 4, but in this section the event is observed from the viewpoint of the intact converter adjacent to the tripped converter.

5.6.1 Loop current measured at load converter

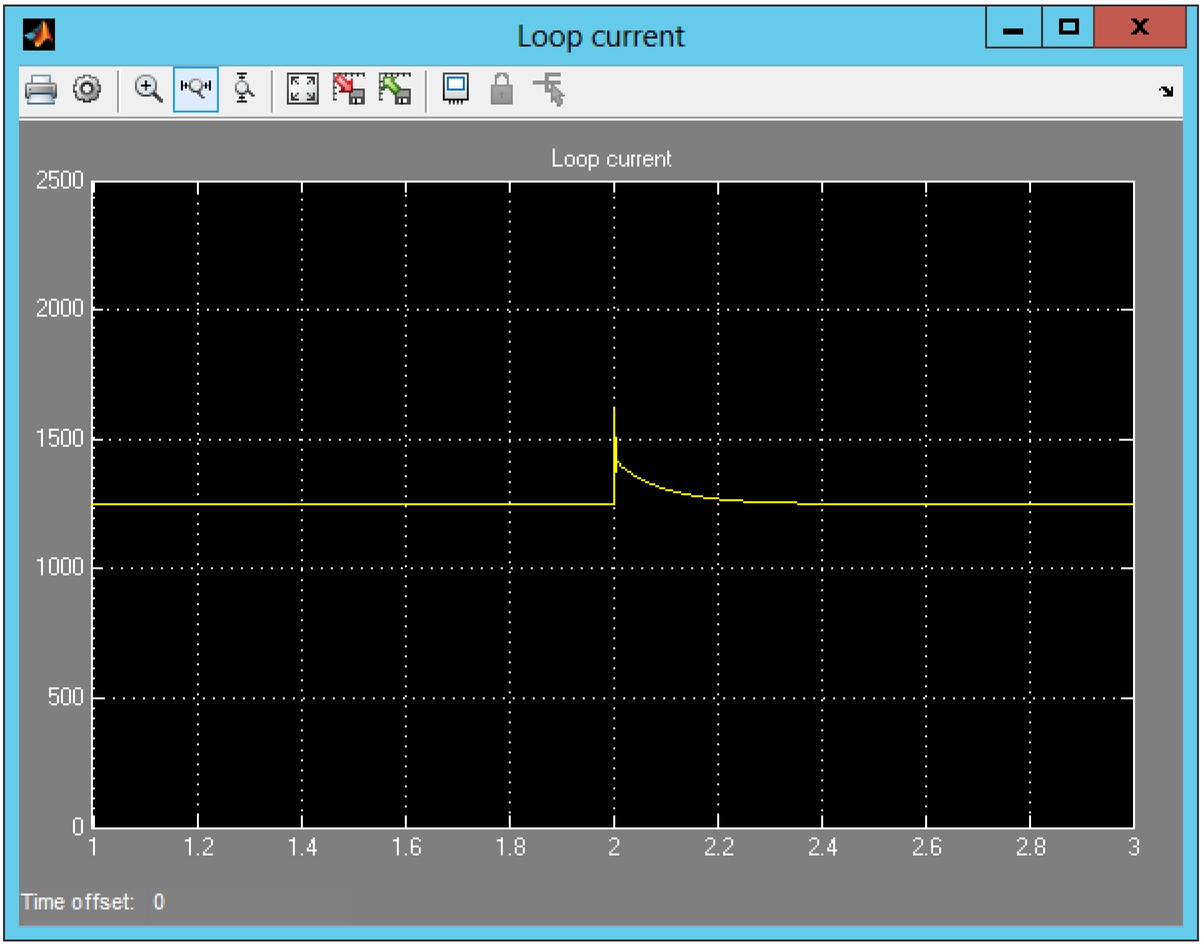


Figure 35 – Loop current measured at load converter.

This intact converter is subjected to the same loop current observed at the tripped converter.

5.6.2 Capacitor current

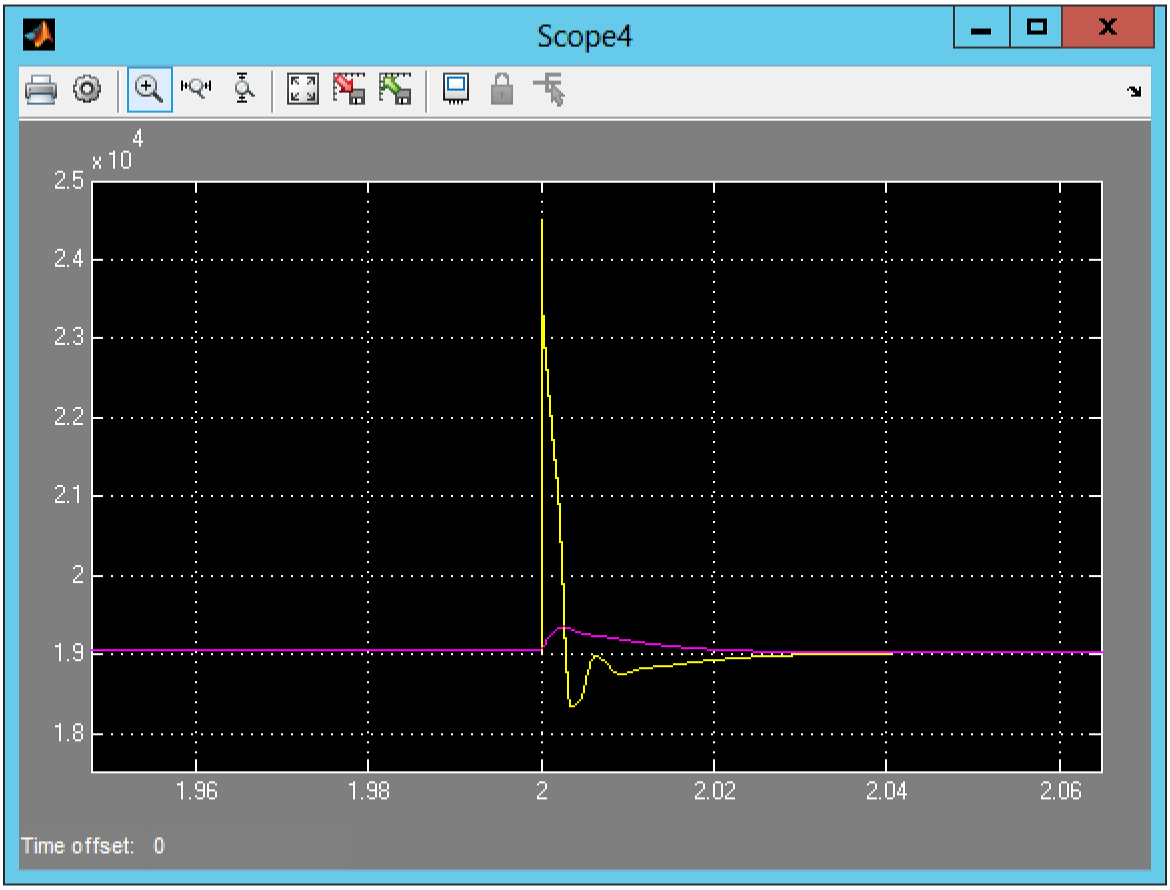


Figure 36 – Detail of transient voltage over the capacitor in load converter.

The initial peak in loop current is also observed in the charging (yellow) current at the capacitor. The peak results in an over voltage at capacitor. The control system compensates by reducing the effective charging current until the capacitor voltage returns to the reference value.

5.6.3 Converter voltage over loop

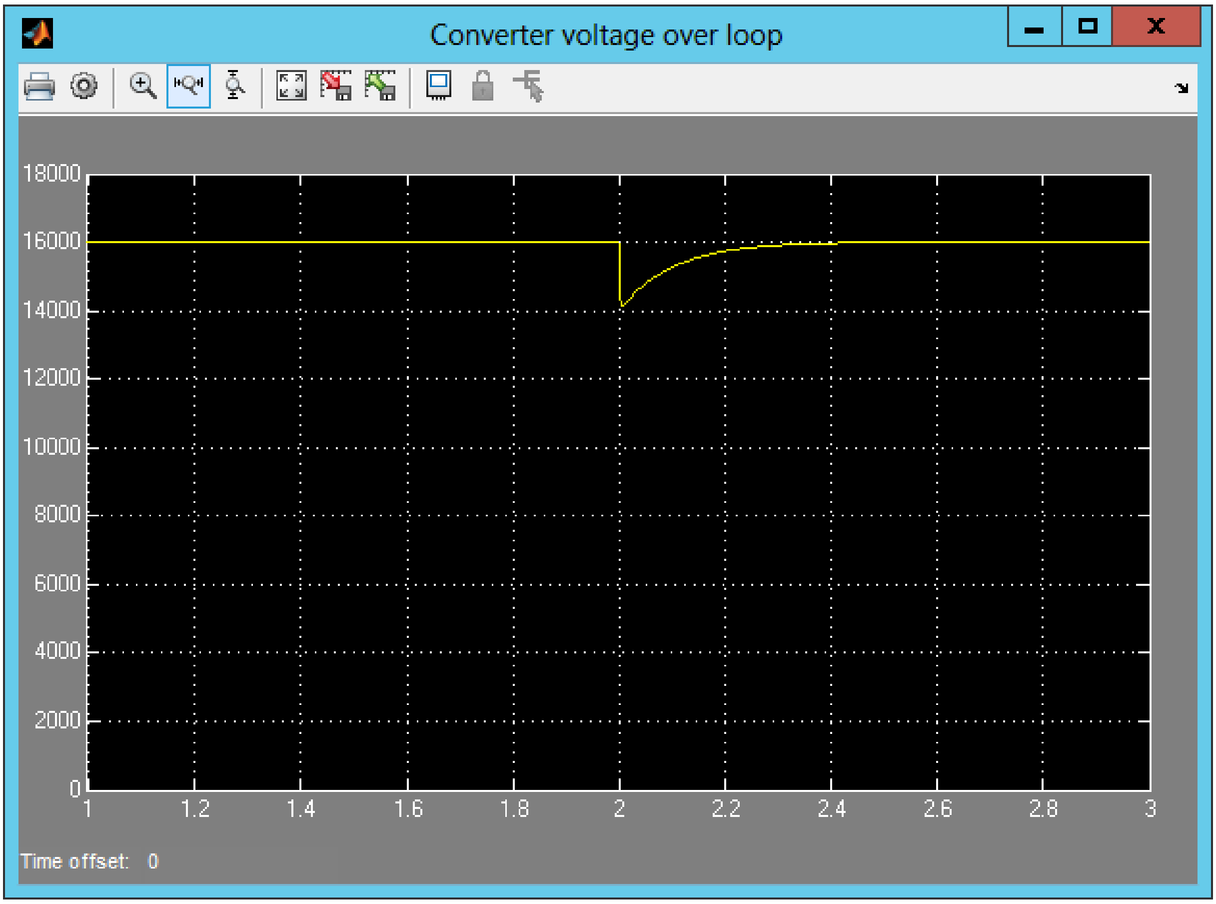


Figure 37 – Apparent voltage applied by the load converter to the main current loop.

The temporary increase in loop current is compensated by an equal increase in voltage over loop, thereby maintaining constant power flow. The control action caused by capacitor voltage transient is not observable, as it lasts for a very short duration compared to loop current transient.

5.6.4 Source voltage

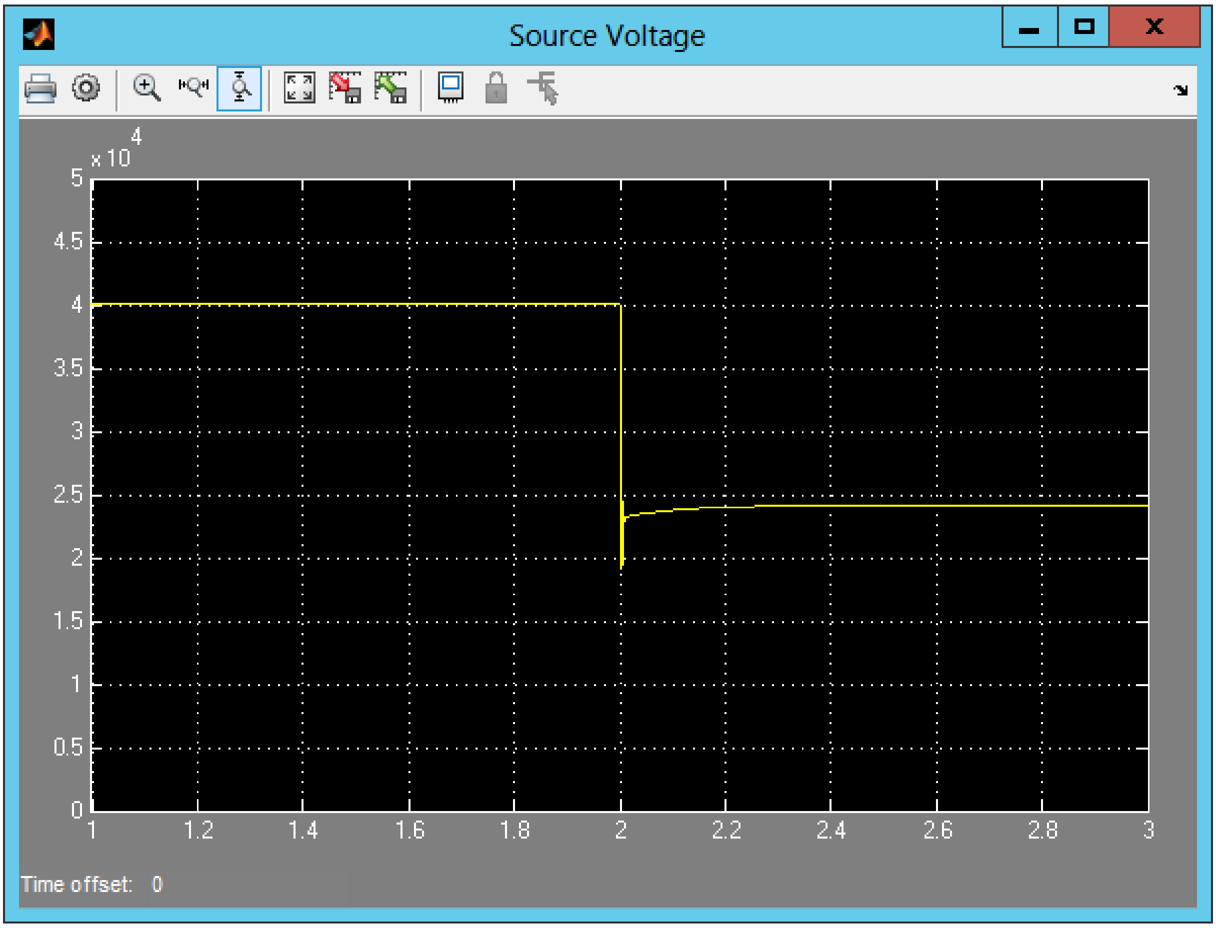


Figure 38 – Voltage measured over source converter.

The source converter will experience the step reduction in voltage from the tripped converter (16 kV), as well as the voltage dip over the adjacent converter (2 kV). In addition to the voltage changes caused by the load converters, the source also observes some initial transients that can be attributed to the initial transients in loop current, after the initial peak.

Peak values on the main loop observed in Scenarios 4 and 5 are not present in Scenario 3 where the DC-DC chopper remains in operation. The continued switching in converter works to reduce initial peak values.

5.7 Scenario 6: Fault ride through in switched model

This scenario uses a switched model for Converter 1. The converter station represents a single sub-module, as opposed to aggregate converters representing multiple sub-modules in previous scenarios. The DC-DC chopper is implemented as a half-bridge design using IGBTs for controlled switches. The PWM control system will determine switching states by comparators, triangle signals and the same PI-regulated feedback loop employed in previous scenarios.

The total system power is now 21 MW, compared to 40 MW in previous scenarios.

The event simulates a failure of an IGBT where the faulty component is left in a non-conducting state (open circuit). The control system and the remaining intact IGBT will continue operation.

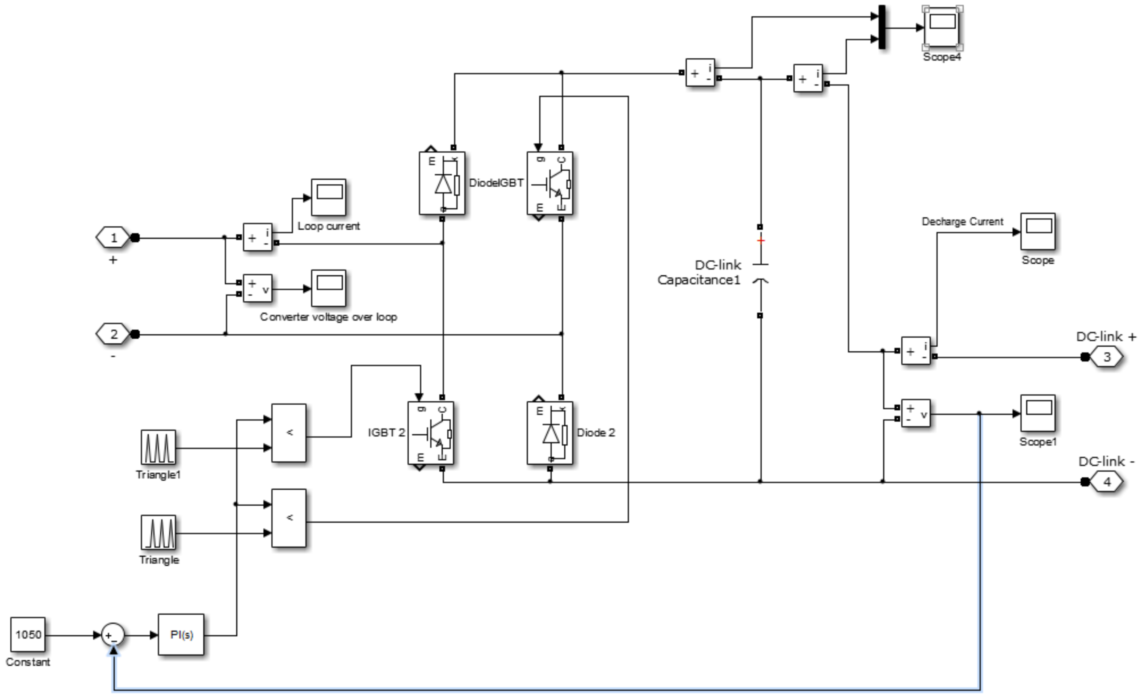


Figure 39 – Switched simulation model of half-bridge DC-DC converter. The model is used in Scenario 6, 7 and 8.

5.7.1 Branch currents in power electronic components

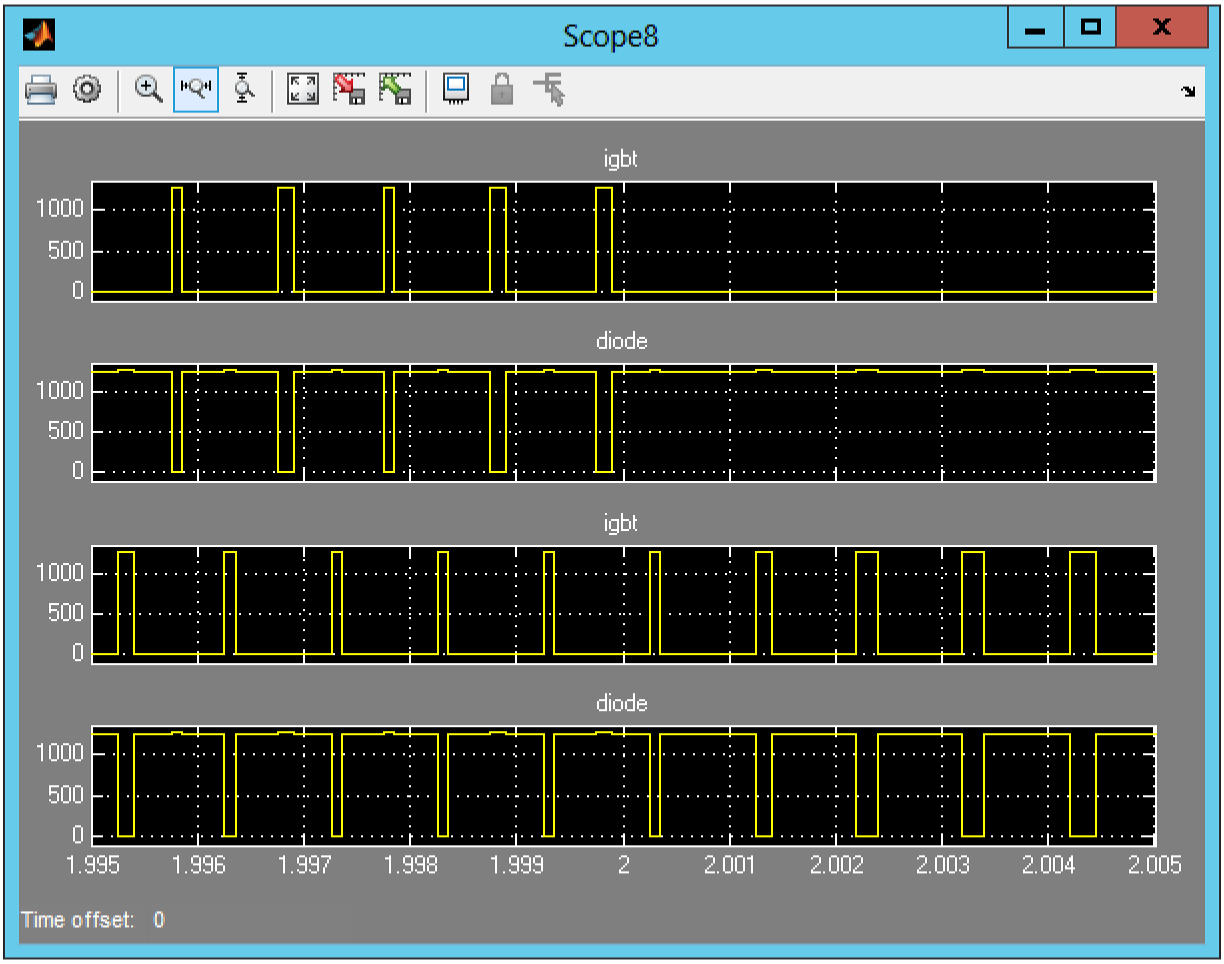


Figure 40 – The commutation of power electronic devices before and after the component failure.

At t=2 one of the IGBTs will stop conducting as a result of a component failure. Notice how the duty cycle of the intact IGBT will increase after the fault. This is the response of the control system to regulate capacitor voltage.

5.7.2 Capacitor voltage

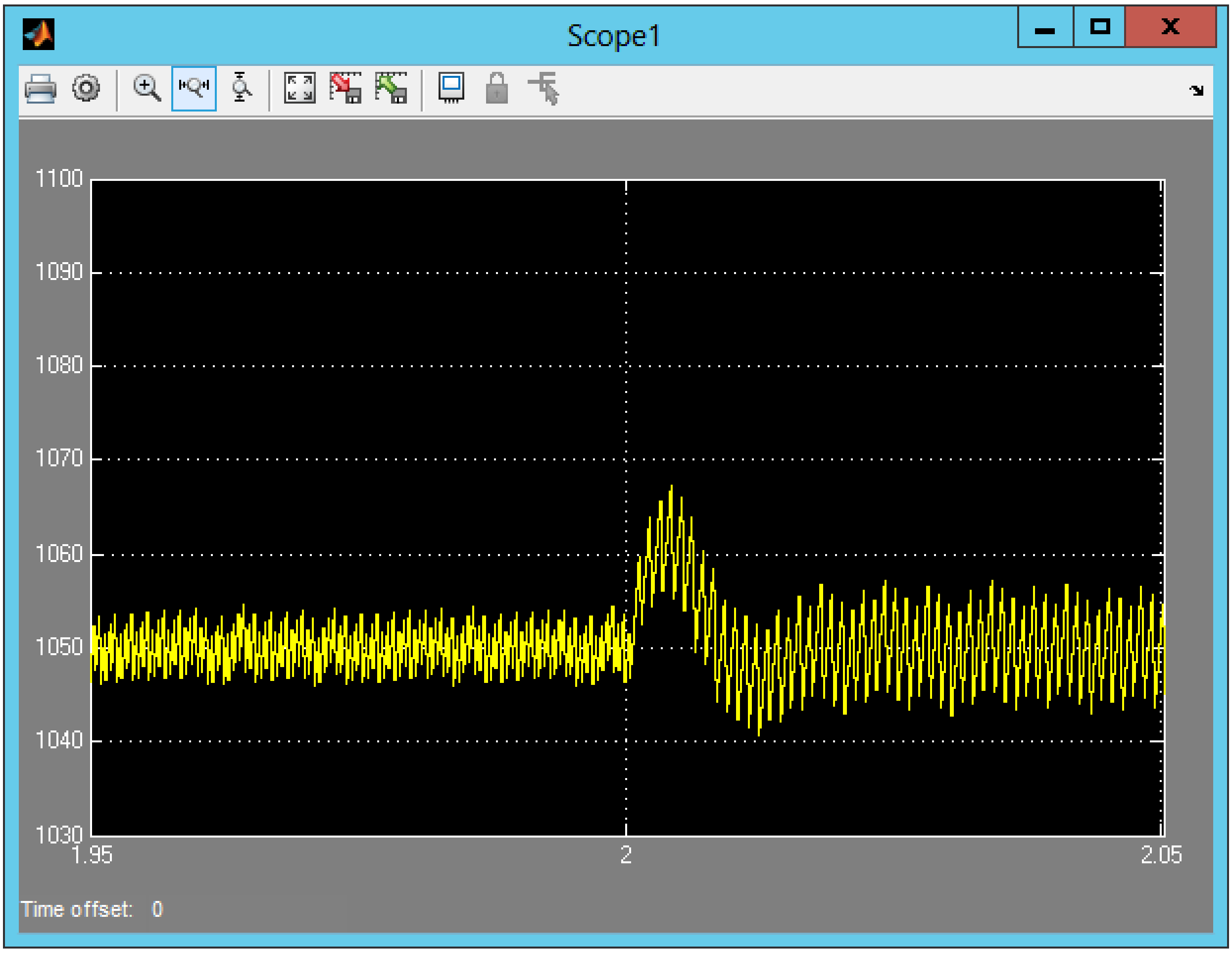


Figure 41 – Voltage measured over the capacitor.

Although, the capacitor undergoes a short term overvoltage at the moment of the fault, a fast acting control system regulates the voltage back to the reference value. The component failure causes no steady state error, and the converter continues to supply power to downstream loads.

The voltage ripple is increased the component failure.

5.7.3 Controller response

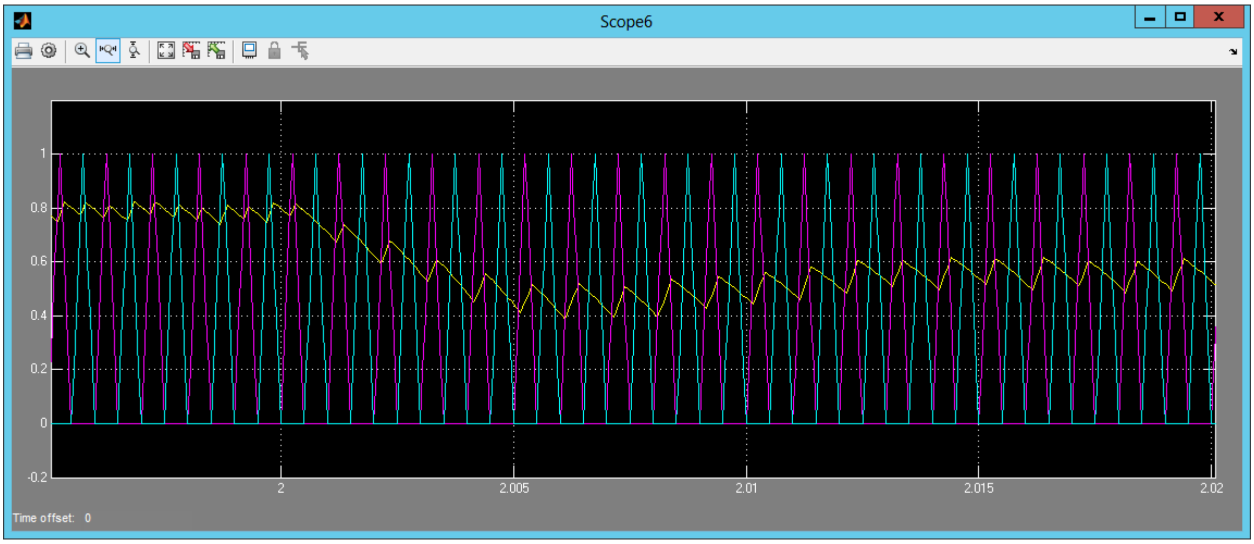


Figure 42 – PI regulator output signal (yellow) and triangle signals used in comparators.

After the fault, only the effect of the comparator at the intact component (purple triangle signal) contributes to regulate the capacitor voltage. The total number of switching actions in the system is reduced to half, as can be observed by the regulator output (yellow). The duty cycle of the intact converter is increased, as can be observed by the new steady state value of regulator output reaching a lower value.

The component failure causes loss of functionality, as the capacitor can no longer be discharged through the DC-DC chopper.

The converter remains in operation and continue to supply load power. Since the feedback control action is sufficient, no detection mechanism of the component failure was necessary.

A challenge is presented by the scenario. For a given load, the controller output signal is reduced after the component failure. If the load before the fault had been below 50% of maximum load, the required (combined) duty cycle of IGBTs would have been exceeding 50%. The limitation in the model is the triangle signals which only apply 50 % duty cycle when the controller signal is zero. This challenge will be further investigated in Scenario 7.

5.8 Scenario 7: Fault ride through at 40% load

Scenario 7 is based on Scenario 6, but models a different load connected to the switched converter. The purpose of this event is to show how the control system will react to operation with only one intact IGBT while the load power is below 50%.

The total system power is now 20.4 MW, with the switched converter model running at 40% capacity.

5.8.1 Capacitor voltage

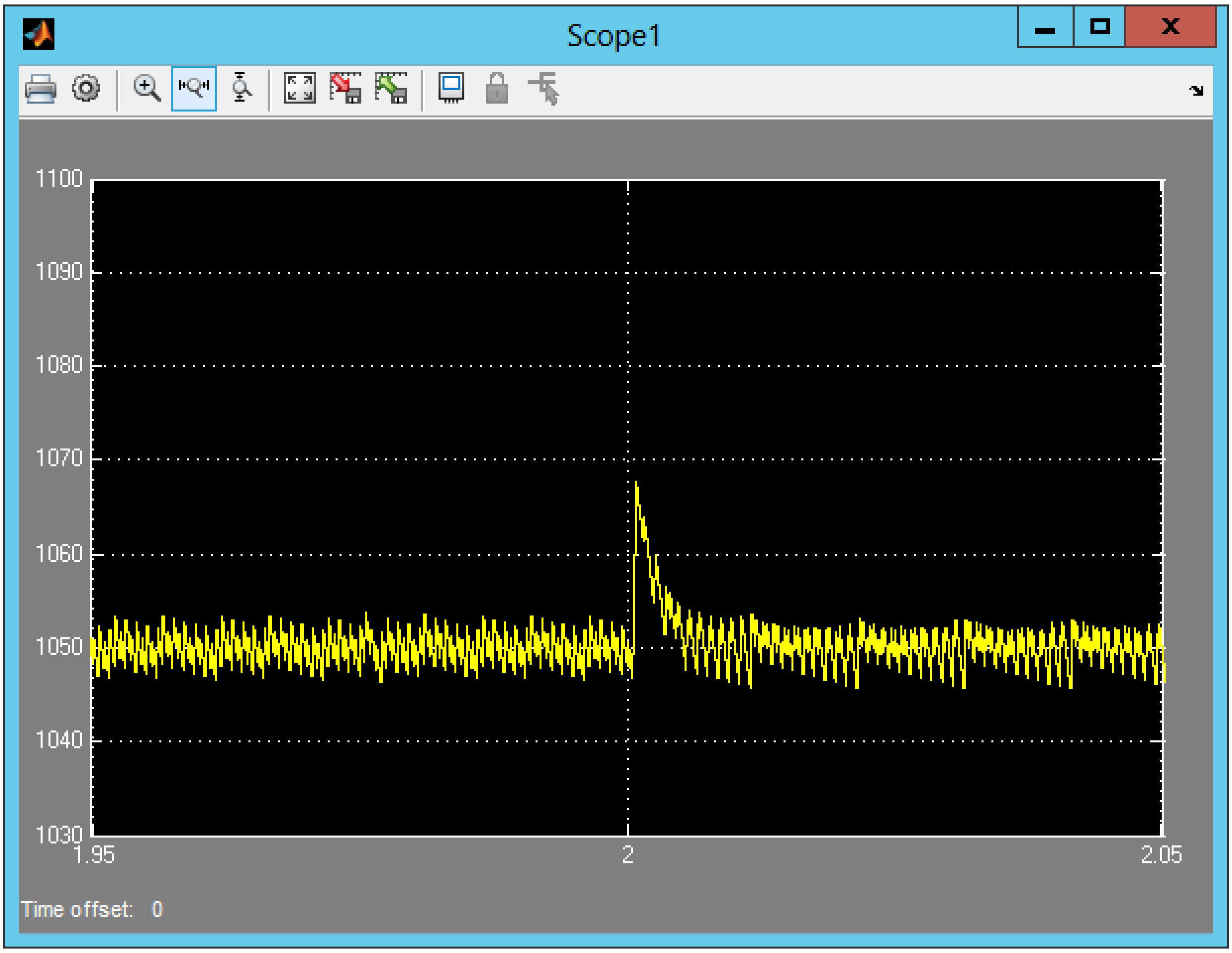


Figure 43 – Voltage measured over the capacitor.

Although the capacitor undergoes a similar transient as in Scenario 6, the peak is higher in magnitude in Scenario 7. The voltage ripple is also higher in amplitude, both before and after the component failure. The capacitor remains energized after the fault, and the converter continue to supply load power.

5.8.2 Controller response

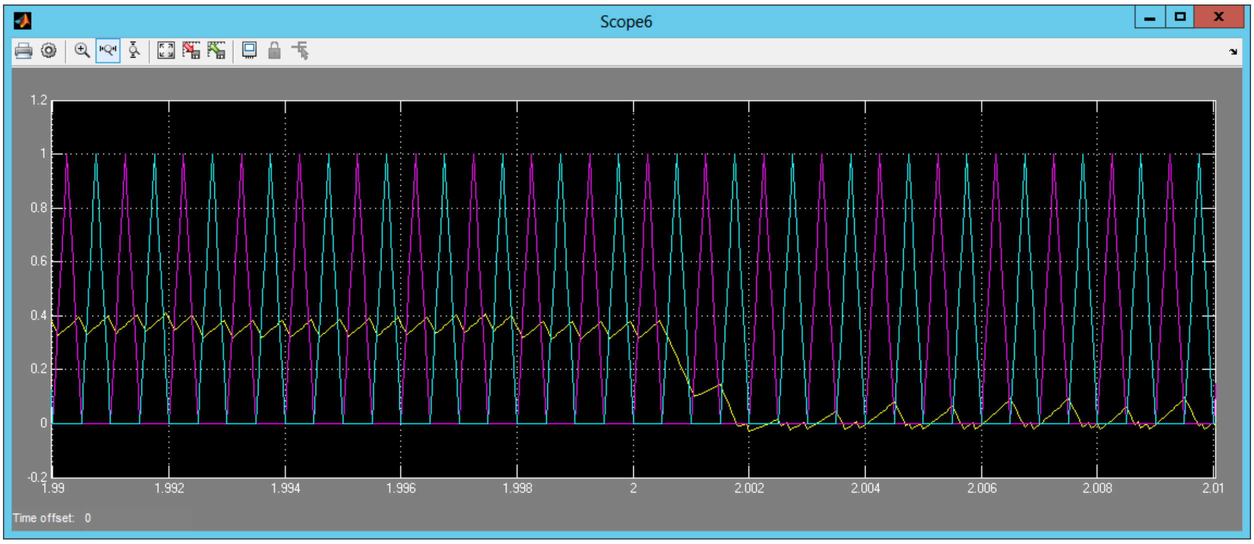


Figure 44 – PI regulator output signal (yellow) and triangle signals used in comparators.

The controller is able to alternate between positive and negative values around zero, thus the effective duty cycle of the intact IGBT will exceed 50%.This enables the controller to reach a form of steady state value with significant distortion after the component failure.

5.8.3 Switching pattern

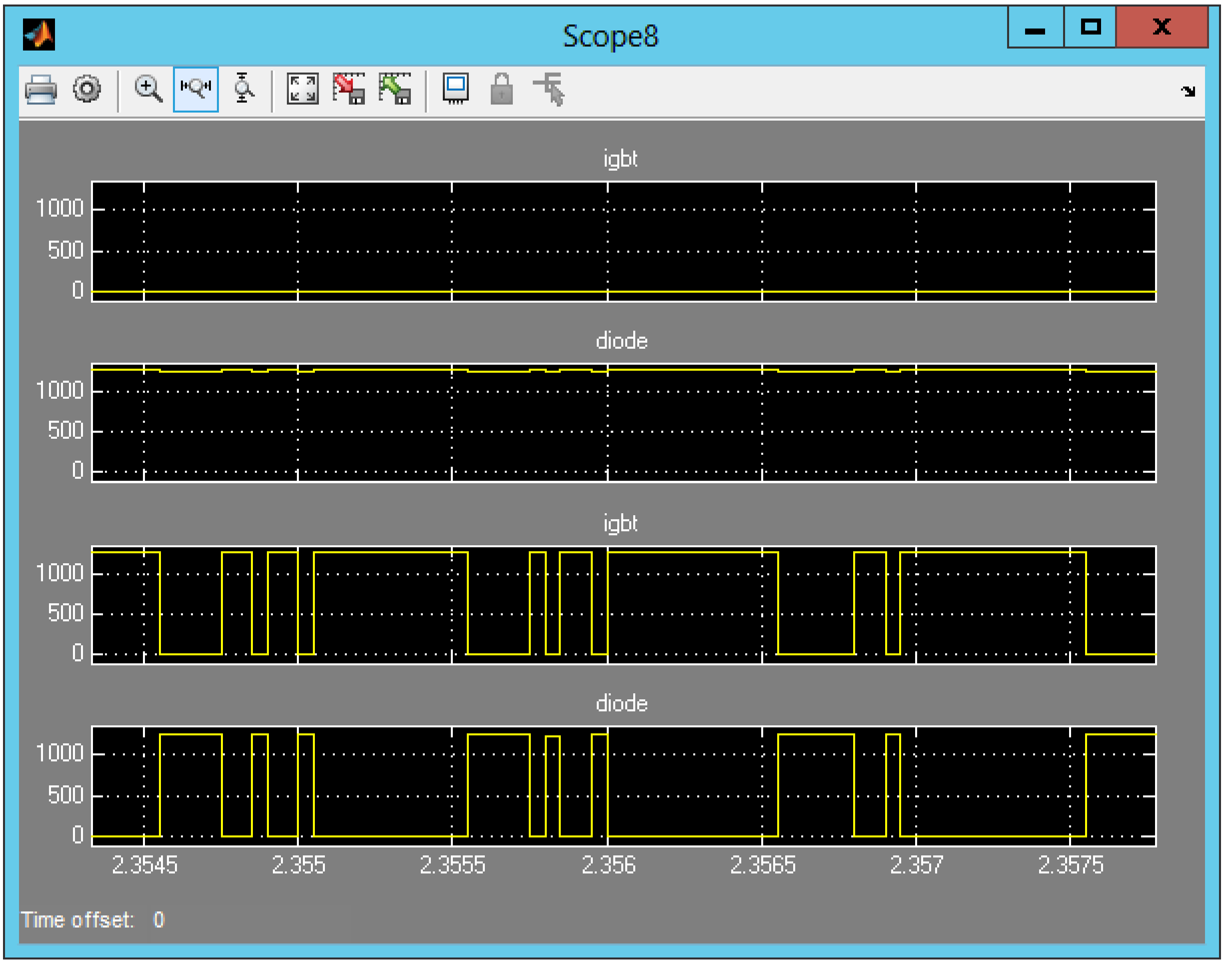


Figure 45 – Switching pattern after component failure, in new steady state.

Because the controller output signal alternates between positive and negative values around zero, the average duty cycle is above 50%.

To create a switching pattern where the pulse widths are more evenly spaced, the half-period triangle signal used in the comparator can be replaced. The change in triangle signal can be either permanently or can be performed upon detecting a component failure. This modified control pattern is further investigated in Scenario 8.

5.9 Scenario 8: Fault ride through with modified switching pattern

The event modeled in Scenario 8 is similar to Scenario 7, but the control system has been modified to employ a triangle signal extending to negative values.

5.9.1 Controller response

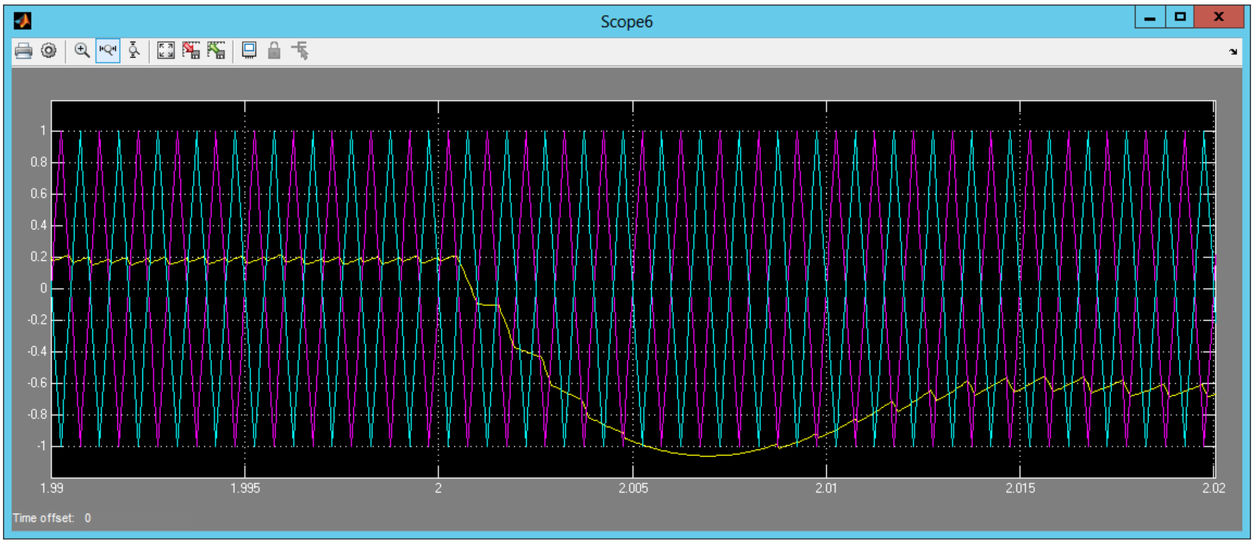


Figure 46 – PI regulator output signal (yellow) and triangle signals used in comparators.

Compared to Scenario 7, the control system uses a longer time before it reaches a steady state value.

5.9.2 Switching pattern

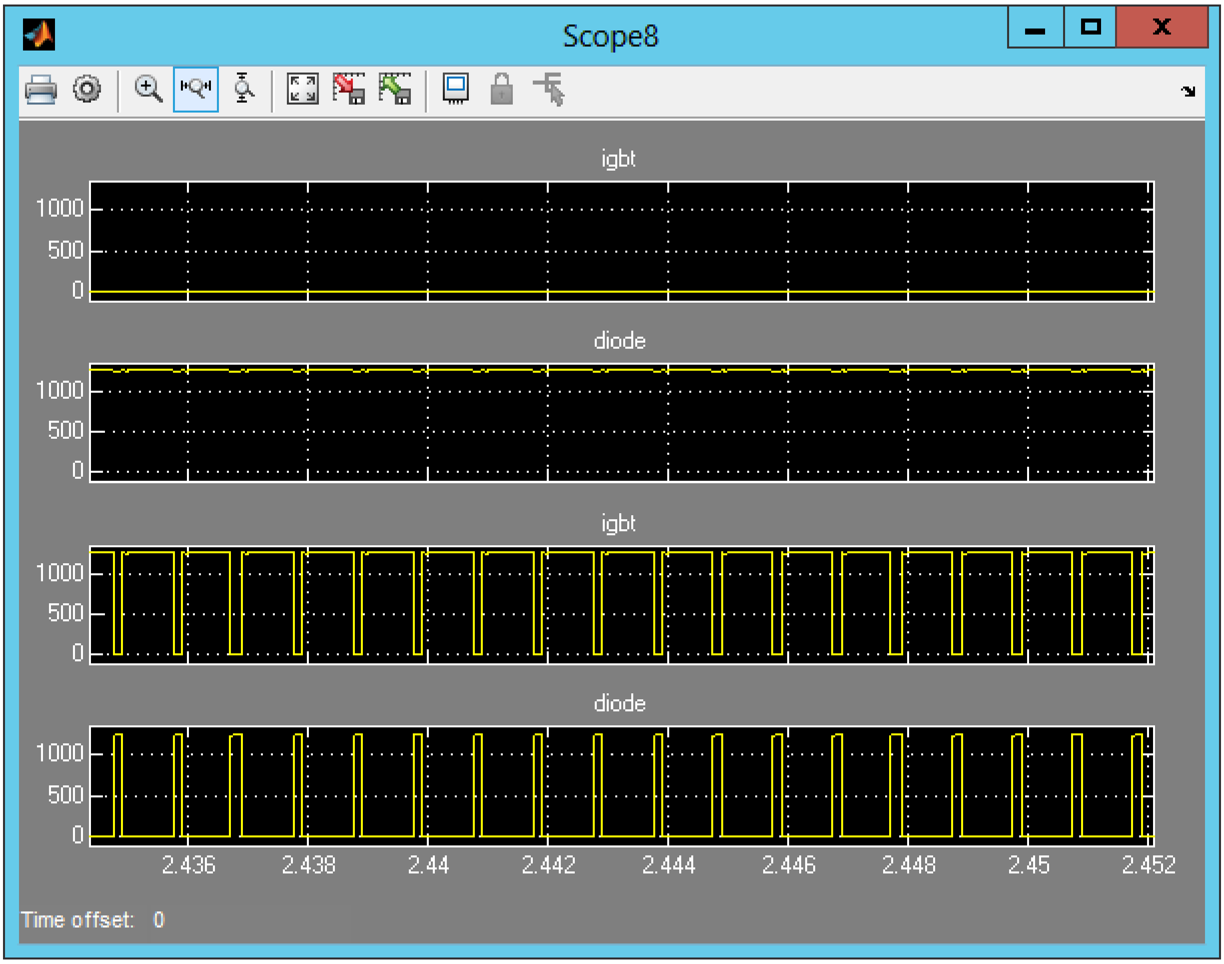


Figure 47 – Switching pattern after component failure, in new steady state.

The pulse widths are evenly spaced, implying that using a triangle signal extending to negative values improves the switching pattern in the new steady state.

5.9.3 Capacitor voltage

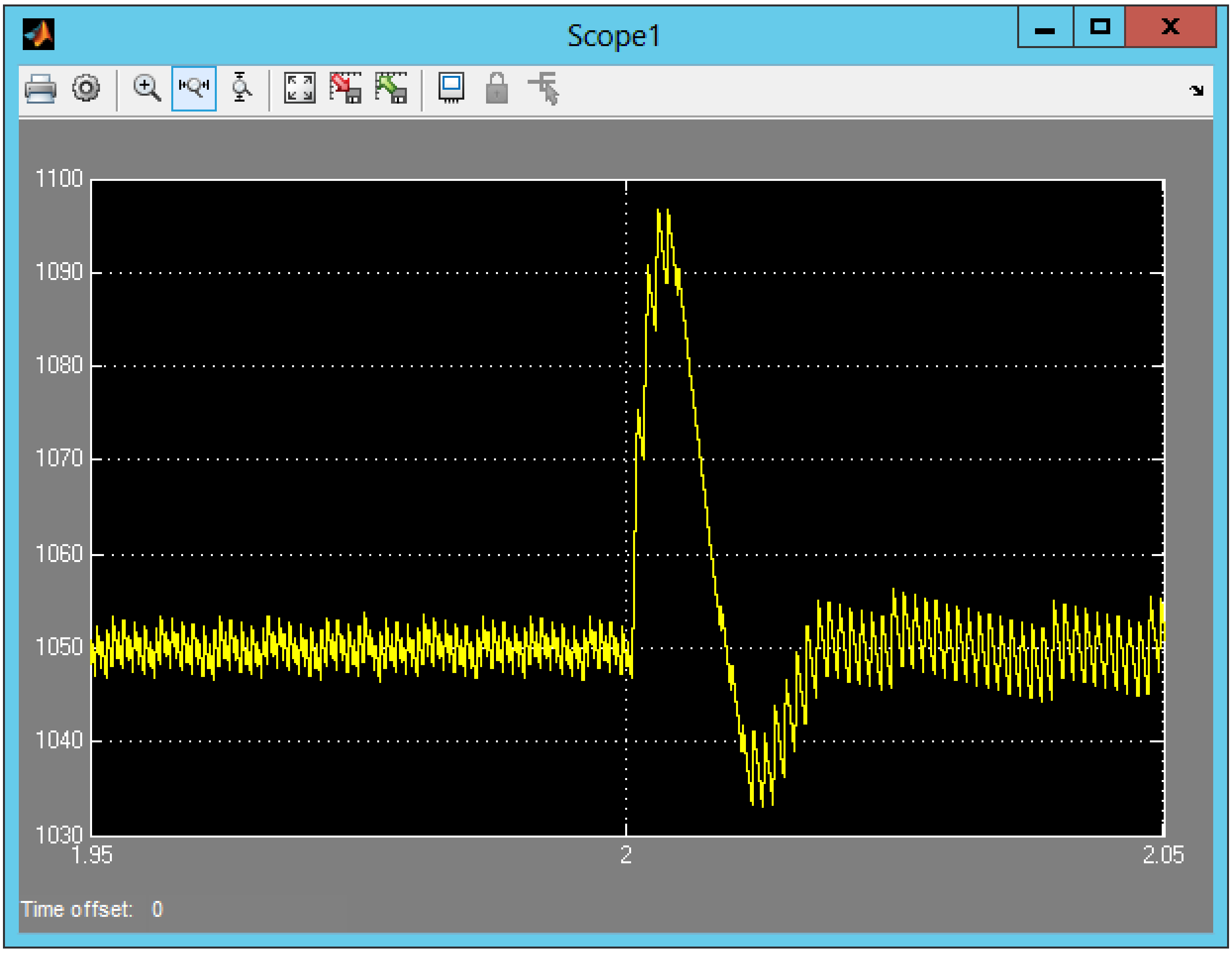


Figure 48 – Voltage measured over the capacitor.

The transient voltage at capacitor (Figure 48) illustrates the drawback of the modified control system. The voltage peak is larger and the response time is longer than it was in Scenario 7.

To conclude, the control system used in Scenario 6 and 7 enables the system to quickly respond to system transients, while the control system used in Scenario 8 improves the steady state switching after an IGBT failure.

The optimal combination will be to employ the first control system as long as the system is fully intact. After a component failure is detected, the system will wait for the transient to pass before it changes to the control system used in Scenario 8.

5.10 Analysis and design verification

The simulation results in the Scenarios 1 through 8 show that the system is capable of operating continuously in steady state. The converters and their control systems will solve a DC power flow problem for a given demand. The system is also considered stable the regard that it will find a new steady state solution to the power flow problem after a change in power demand. Each converter is capable of adjusting to a disturbance or component failure elsewhere in the system and will continue operation.

These three properties hold for an implementation of MSDC where each converter is controlled autonomously without any signals communicated between them. The article [7] specifies that the system will be implemented with communication between sub-modules, and implies that information on power demand will be transmitted. The article suggests that the information will be used for manipulating reference signals in the control systems, and for dealing with system level faults. The communicated signals could possibly improve operation performance, add additional functionality, or simply be utilized for monitoring purposes.

Instead of communicating power demand between converters, the value of instantaneous loop current is sufficient to balance power demand with generation. Analogies are made to conventional AC grids, where frequency droop is used to achieve power balance, and to DC grids, where system voltage is used similarly. Loop current can be observed at any point in the system, and the value will not differ significantly between components around the loop. The source converter is required to measure the loop current directly (for example with a LEM Hall effect current sensor or other type of transducer), while the load converters can observe the loop current indirectly through measuring voltage over capacitor.

As demonstrated in Scenarios 3 through 5, the MSDC system is capable of continuing operation in the event that parts of the system are disconnected. Scenario 3 illustrates how the downstream power consumers can be disconnected while the transmission loop and the DC-DC chopper continue to operate in a state that is ready for reconnection at any moment. Scenario 4 and 5 demonstrate how one converter can trip and isolate itself from the transmission loop when a fault is detected. The disconnection does not require the loop current to be broken, confirming the claim in [1]. The remaining components in the system manage to ride through the event without interruption of power delivery.

In Scenario 1, 2 and 3 the change in system state was caused by changes outside of the observed converters. The same is true for Converter 2 as it was observed in Scenario 5. In all of these events the converters react appropriately without requiring any external signal to change operation state. Neither converter had any built-in monitoring to detect the events beyond the effects on the variables regulated by feedback control. In all cases the converters remain energized during and after the disturbance, and remain responsive to further dynamics in the system. In the events of Scenario 6, 7 and 8, the change in system state was caused by an internal fault in the observed load converter. The converter continued to remain in operation without any detection mechanisms or external commands, but the performance could be improved by modifying switching control after the fault and initial transient. If this functionality of detection and altered control is implemented, the reaction time is not critical to the ability to continue operation uninterrupted.

If comparing Scenarios 1 with Scenarios 3-5, they illustrate how rapid reduction in load power results in less over-/undershoot of source voltage than a similar increases in power would cause (if ignoring initial peaks). The amplitude of these transients depends on the amount of load power connected after the fault, as well as the magnitude of current deviation.

When comparing durations of transients and time constants of convergence, it shows how the load converter’s ability to regulate internal capacitor voltage is quicker than the source converter’s ability to regulate current. Rapid response in load converters is necessary to prevent the connected inverter from tripping from over-/undervoltages. The response time of source converter can probably be improved by modifying the control system, for example by implementing a state observer as part of the source controller. Communicating the system power demand to the source converter and using this in feed forward could also improve response time. Further testing is required to make any conclusions.

The use of a switched model in Scenario 6, 7 and 8 illustrate the effect various parameters have on capacitor voltage ripple. The low load scenario has larger amplitude of ripple and higher peak voltage in a transient than the full load case. After events where a component fails and the converter continue operation, the ripple is more severe after the fault. When applying the control system investigated in Scenario 8, the voltage peak and convergence time were larger than in the former scenarios. These observations should also hold for a discussion of voltage ripple on the main loop. In a stack of sub-modules where the switching states are phase shifted, the failure of one component would increase the total ripple over the stack.

5.10.1 Summary of verification

The system is convergent with the described control system.

The system is stable against the disturbances described in the scenarios.

Components can trip and disconnect from the system without breaking the loop current.

A converter module has redundancy to withstand the failure of a single power electronic controlled switch, as long as it will not conduct current after failure.

The system can operate without transmitting signals between converter stations.

6 Further work

The control system of the MSDC architecture can be studied on a more detailed level. The use of communication between converter stations has been presented as a mechanism to improve system dynamics and add functionality. The stand-alone operation of converters in a system without communication can possibly be improved by introducing state observers.

Reliability in cables and connectors must be shown sufficient if the technology shall see commercial success. Operator experience can be used to determine if the added redundancy in converter stations outweighs the MSDC architecture's dependency on cables and connectors.

Despite being a considered a critical component for the architecture, there is little information available on the topic of cables in MSDC. The system design could possibly be improved upon by developing a cable strategy particularly suited for the converter technology. This includes exploring different ratios of L/R in the transmission circuit, how it will influence system stability and transients and how it can be manipulated in cable cross section, with the inclusion of reactors, and by altering cable paths and distances between parallel cables.