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# High-Power, Resonant DC/DC Converter for Integration of Renewable Sources

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***Abstract*—This paper studies practical design aspects of a high-power DC-DC converter which might be employed with renewable power sources like large offshore wind farms. The component selection and losses are studied for a *6.8kV/100kV, 5MW* step-up DC/DC converter. It is concluded that inverter-grade thyristors offer overall advantages because of ability to operate at high switching frequencies. The converter operates at all zero current switchings and therefore an increase in the operating frequency has minimal effect on the efficiency. The detailed converter modelling at switch level indicates that the converter efficiency will be around *96-97%*. Better efficiencies are possible with phase-control thyristors, but this would come at the expense of significant increase in the size and weight of the passive components. The dimensions and weight of the crucial passive components are calculated and the largest air-core inductor may weigh around *610kg*. The converter responses are simulated for reference step changes and the detailed steady-stet curves are analysed. The converter is further tested for the worst case fault conditions. The simulations indicate that the converter will not propagate fault currents, if the converter components are adequately selected.**

***Index Terms*—DC-DC power conversion, thyristor converters.**

## I. INTRODUCTION

In the MW power range there has not been much practical applications of DC-DC converters because of the insufficient market need and the lack of suitable technology. In recent years, however, the market demand for DC-DC connection has significantly increased considering proliferation of power sources that generate DC [1,2]. The DC power sources that are approaching power levels of multiple MWs include: fuel cells, photovoltaics, batteries and redox flow. Also, all variable speed machines (like wind generators or small hydro generators) may be viewed as DC sources if the last converter stage is removed [3]. Furthermore, majority of electrical storage and load leveling devices use a DC storage media (batteries, supercapacitors, capacitors, superconducting magnetic energy storage etc). Many of these DC sources utilise very low voltage basic cells, or require wide variation of DC voltage, and their integration into the power grid has traditionally been difficult.

The rapid development of HVDC (High Voltage DC) transmission technologies is also driving demand for DC-DC converters at highest powers. The recently developed HVDC light (HVDC with Voltage Source Converters) [4] has already been implemented in dozen interconnections and it is being promoted as a very suitable solution for integration of renewable power sources. A suitable MW size DC-DC converter would enable development of multiterminal HVDC. The recent development of offshore renewable sources creates scenario of multiple DC sources and the favorable conditions for submarine DC transmission, which require DC voltage stepping at MW power levels. A high-power DC transformer would also aid in development of FACTS (Flexible AC transmission systems) technology. It can expand connection of FACTS elements (like STATCOM or UPFC) to a wide range of DC sources.

The DC-DC converters have been extensively utilized at low power levels and myriad of topologies exist. However most of these technologies are not suitable for scaling up to MW power levels. The limitations are linked to the nature of the high-power switches, the operating frequencies, efficiency, switch utilization and others.

The conventional, unidirectional boost converters [5] can not achieve gains larger than 2-4 or higher powers because of difficulties with the output diode. There have been attempts to develop the flyback and forward converters [5-7] at higher power levels; nevertheless some series inherent limitation in terms of stepping ratios and power levels have been demonstrated [8]. Reference [1] studies scaling up to *5kW* with stepping ratio of *5* and [2] describes a *100kW, 14kV* forward converter. However these converters utilize MOSFETs as switches with around *10kHz* frequency, which gives low prospect for further increasing to MW power levels.

The switched capacitor converters have been proposed as a method of achieving high DC boost without transformers/inductors [9]. On the downside, the switched capacitor converters are modular, where each module increases output voltage only by the value of the input voltage. To achieve stepping ratio of say *10, 9* modules are needed and over *18* switches, which implies significant losses and complexity.

A new step up DC-DC converter has been proposed recently [11,12] which achieves voltage boost without intermediate transformers. It has been demonstrated that this converter can achieve very high step-up gains with a MW range test systems.

This paper investigates the practical aspects of the converter concept from [11] and explores the application with a large offshore wind farm. The goal is to study the component selection the converter losses and faults. These practical aspects have enormous importance with practical applications at MW power range. The DC/DC converters that do not utilize

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intermediate transformers, will always require increased rating of electronic switches which is typically $nxP_{rated}$ , where *n* is the voltage stepping ratio. Higher size of switches has negative consequences in terms of costs and losses. Nevertheless these penalties should be carefully weighted against the benefits that direct DC/DC conversion may bring.

## II. APPLICATION WITH AN OFFSHORE WIND FARM

AC transmission has serious limitations with submarine cable systems and maximum cable length is limited to around *50km*. DC transmission has no limitations in length and further advantages over AC transmission exist, including: smaller cables, lower losses, better control, no need for reactive power.

The main shortcomings with DC transmission networks are related to cots of converter, difficulties with voltage stepping, and difficulties with fault current limiting.

Figure 1 shows a *300MW* wind farm consisting of *60, 5MW/4kV* wind generators. The generators operate at variable speed and they are equipped with VSC (Voltage Source Converter) rectifiers which generate *6.8kV* DC. Each rectifier is connected to a DC/DC converter that steps up the DC voltage to *100kV* which is sufficiently high for long distance submarine transmission. The wind farm does not need AC iron-core transformers at the offshore platforms. The proposed topology provides all benefits of DC transmission with simplicity of offshore systems.

## III. HIGH POWER STEP UP DC/DC CONVERTER

### A. Low voltage circuit design

The theoretical basis for the step-up DC/DC converter is researched in [11,12] and only a summary is given here. Figure 2 shows the high-power resonant step-up unidirectional DC-DC converter topology. All switches should have reverse blocking capability, but turn-off capability is not required, and therefore thyristors are suitable. The filters ($L_{f1}$, $C_{f1}$ and $L_{f2}$, $C_{f2}$) are not essential but they reduce harmonics and they are further discussed below.

The capacitor $C_r$ is rotated by sequentially firing $T_1$ and $T_2$ pairs at *0.5* duty ratio. The operating frequency is used as the control input. The nominal switching frequency $f_s$ can be selected considering that the maximum switching frequency is:

$$f_{s\max} = 1/(2T_{off}) \tag{1}$$

where $T_{off}$ is the turn-off time for the thyristors. The main converter design equation is given as:

$$\frac{I_2(V_2 - V_1)}{V_1 V_2} = C_r f_s, \tag{2}$$

The above equation indicates controllability through frequency $f_s$, and applies to both: continuous and discontinuous mode.

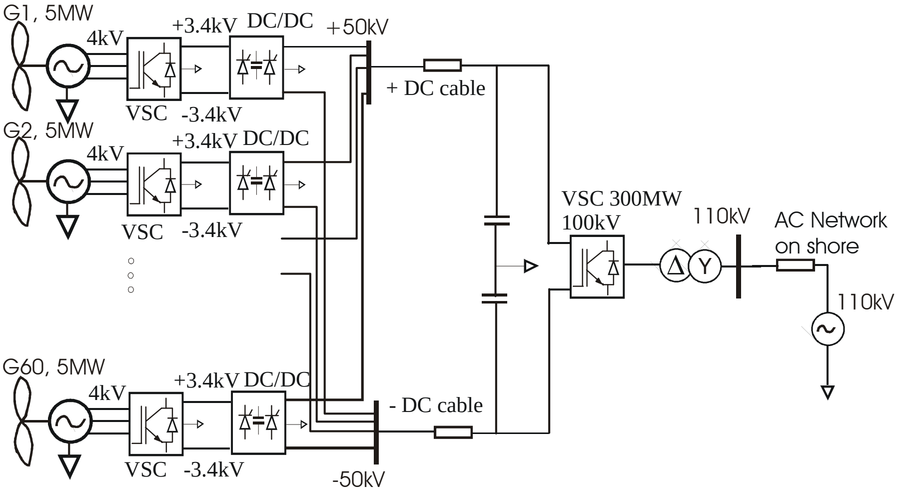

Figure 1. 300MW wind farm with DC/DC converters offshore.

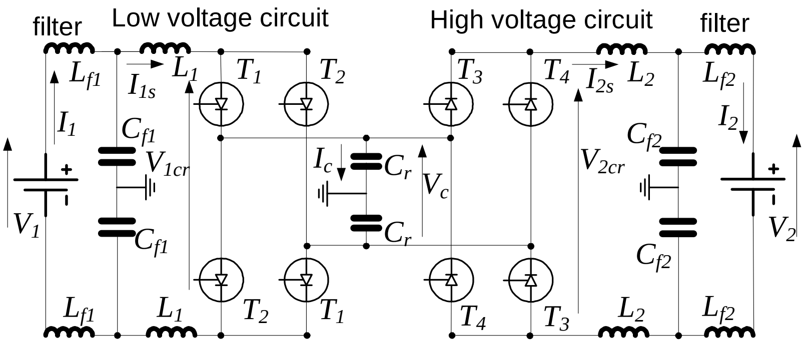

Figure 2. High-power step-up unidirectional DC/DC converter.

Assuming that $f_s$ and the power/voltage levels are known ($I_2$,$V_2$,$V_1$) then $C_r$ can be determined from (2). The operation in discontinuous mode, close to the border with continuous mode may offer overall advantages. With $C_r$ known, the value for the resonant inductor at the border of discontinuous mode is:

$$L_1 = 4/\left(\pi^2 f_s^2 C_r\right) \tag{3}$$

The main advantages of the converter are:

- The converter design equation (2) shows very weak dependence on the gain ($V_2/V_1$), and the converter can achieve very high output voltages. The control input ($f_s$) affects the power transfer, almost equally at any gain.
- In discontinuous mode all switchings are at zero current, and therefore losses/stresses are minimal.
- It is suitable for MW-range power transfer because of the use of thyristors, and low switch stresses.
- The reverse recovery losses are also minimal and therefore only the conduction losses are applicable.
- In general, it is not vulnerable to commutation failure.

On the down side, discontinuous mode implies higher harmonics and the frequency of dominant harmonics will reduce as the power transfer reduces. At low switching frequencies, the cost of filtering may be high.

### B. *Selection of switches*

The turn off time for switches $T_1$-$T_2$ determines the operating frequency. The inverter-grade thyristors have the turn off time of the order *50-100μs* and the maximum voltage rating of around *2-3kV*. The Silicon Power thyristor C613 (*2.1kV, 800A, 50μs*) would allow theoretically maximum operating frequency of *10kHz*. In order to allow robust operation under disturbances/faults some margin is required and the operating frequency of *4kHz* is selected. The higher operating frequency implies smaller passive components. However, the inverter grade thyristors have low voltage rating and this implies high series resistance since *57* units are required for a single *100kV* switch. The overall converter efficiency will be around *96-97%* with the inverter grade switches, as it will be demonstrated below. Table 1 shows all the switch data used in the simulation model.

The phase control thyristors are nowadays available with voltage ratings of over *6kV*. With these thyristors there will be lower series resistance and simulation shows that the overall converter efficiency will be around *98-99%*. However the switch turn-off time is around *400-700μs*, and this implies that the operating frequency will be very low (around *300-500Hz*). With low operating frequency the capacitor $C_r$ and the inductor $L_1$ must be considerably larger as seen in (2)-(3).

If the switching frequency is increased, it is also important to pay attention to the current derivatives during conduction and the voltage derivatives in forward blocking state. In the considered converter all switchings are at zero current and there will be no switching stresses. The current and voltage derivatives will be exclusively determined by the responses of the $L_1C_r$ resonant circuit. Table 2 shows that all the switch stresses are well below the limits for the considered switch C613. Furthermore, there is no need for snubbers.

Considering the switch stresses in table 2 it is concluded that the switches in high-voltage circuit have $V_2$ and $I_2$ rating, whereas the low-voltage circuit switches have $V_2$ and $I_1$ rating. Therefore the low voltage converter needs rating of $(V_2/V_1)xP_{rated}$ where $P_{rated}$ is the rated power. This implies penalty in silicon costs which must be compared against benefits in transmission losses and offshore system size.

The digital simulator PSCAD is used for the converter testing [13]. Since PSCAD accommodates only linear model for the switch losses an approximate linear curve is developed and compared with the manufacturer's data, as shown in Figure 3, with the parameters in Table 1. The equation for the on-state voltage $V_{on}$ for a single switch is determined as:

$$V_{on} = 1.1 + 0.001I \tag{4}$$

Figure 4 shows the converter losses calculated considering the above equation and including further manufacturer's data on off-state losses. The losses in the inductors are also included. It is seen that the total converter efficiency of *96%-97%* can be expected.

TABLE 1 SWITCH DATA IN THE PSCAD MODEL (C613)

| | *T1-T8* |
|---|---|
| *Number of switches* | *57* |
| *On resistance [mΩ]* | *57x1=57* |
| *Off resistance [MΩ]* | *57x0.047=2.7* |
| *Voltage drop [V]* | *57x1.1=62.8* |
| *Extinction time [μs]* | *50* |
| *Forward/reverse voltage [kV]* | *120* |

TABLE 2 SWITCH STRESSES FOR THE TEST SYSTEM AT $F_S$=4KHZ

| | Thyristors T1-T4 | Thyristors T5-T8 | Max.values C613 (Silicon Power) |
|---|---|---|---|
| $V_{peak}$ *[kV]* | *113* | *113* | *57x2.1=120* |
| $I_{av}$ *[A]* | *380* | *25* | *475* |
| *dV/dt [V/μs]* | *25* | *25* | *400* |
| *dI/dt [A/μs]* | *18* | *9* | *200* |

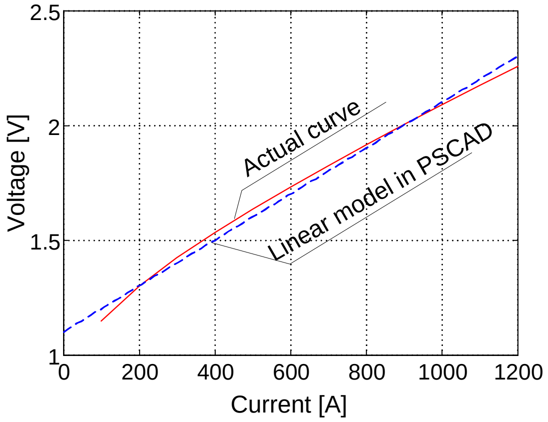

Figure 3. Switch resistance model.

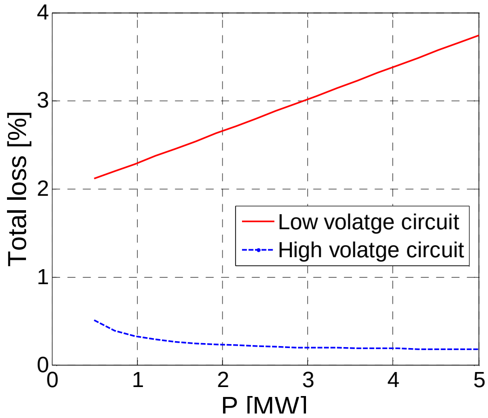

Figure 4. Theoretical converter losses.

### C. *Inductor design*

The inductor $L_1$ is in the high-current path and it plays crucial impact on the converter weight, size and losses. A simple preliminary design is performed assuming a toroidal air-core design, as shown in Figure 5. Air core design can be used at high frequencies but the number of turns will be higher because of low permeability of air. The calculated parameters for both $L_1$ and $L_2$ are shown in table 3. The total weight is therefore around *610kg* for $L_1$ and only *95kg* for $L_2$. The low size, weight and losses of these inductors demonstrate major advantages of the proposed DC/DC converter. Size and weight pay significant role in offshore system costs because of implications for platform costs.

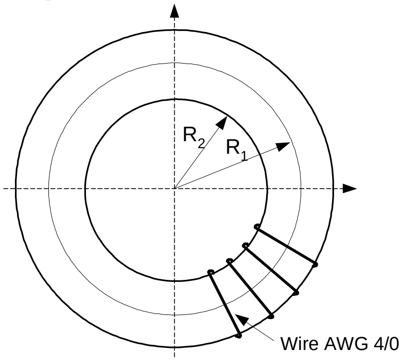

Fig. 5 Air-core toroidal inductor dimensions.

TABLE 3 INDUCTOR DATA

| | *L1* | *L2* |
|---|---|---|
| *Inductance L [mH]* | *3.3* | *2* |
| *Peak current [kA]* | *1300* | *200* |
| *Core size, $R_1$ [m]* | *0.3* | *0.1* |
| *Core size, $R_2$ [m]* | *0.15* | *0.04* |
| *Total resistance [mΩ]* | *11* | *16* |
| *Number of turns* | *3x220* | *264* |
| *Copper mass [kg]* | *610* | *95* |

### D. *High Voltage circuit design*

In general, diodes may be used as the switches in the high voltage circuit in Figure 2 to reduce costs. However thyristors enable better control during faults, as it is discussed below. The turn off time is not essential (since there is no forward blocking) except under most severe faults at high-voltage side. Therefore, the inverter-grade thyristors, as with low voltage circuit, are used, in order to provide complete immunity from faults on $V_2$.

The inductor $L_2$ is not essential for the operation but it will reduce switch stresses and reduce harmonics. Also, increasing $L_2$ improves fault responses. This inductor carries very low current and it will be of small size, as seen in Table 3. It is noted also that increasing inductor $L_2$ increase peak value of the capacitor $C_r$ voltage.

### E. *Filter design*

The dominant harmonic from the DC/DC converter is at frequency $f_s$ and may have large magnitude. At lower powers, the frequency will reduce but the magnitude of the dominant harmonics relative to the DC current magnitude will stay approximately unchanged.

The Low voltage filter ($L_{f1}$, $C_{f1}$) will be determined by the harmonic tolerance of the wind generator and the VSC rectifier. The high voltage filter ($L_{f2}$, $C_{f2}$) will primarily depend on the harmonic tolerance by the high-voltage cable. Note that in a large wind farm there will be further power averaging and harmonic cancelation in the main *100kV* cable.

In the considered test system, the filters are designed for approximately *5%* harmonic magnitude. All the test system parameters including filters are given in the Appendix.

## IV. SIMULATION RESULTS

### A. *Steady-state operation*

A DC/DC *6.8kV/100kV*, *5MW* test converter is developed on PSCAD digital simulator with detailed switch models. The converter is operated in $I_1$ feedback control mode, using frequency as the control input. Figure 6 shows the responses on positive and negative current reference step. Very good and fast controllability is evident.

Figure 7 shows detailed traces for the converter variables at nominal power level. The high-voltage and the low voltage currents are discontinuous which eliminate switching losses. We observe that the peak capacitor voltage is around *15%* higher than $V_2$, which is the result of size of inductor $L_2$.

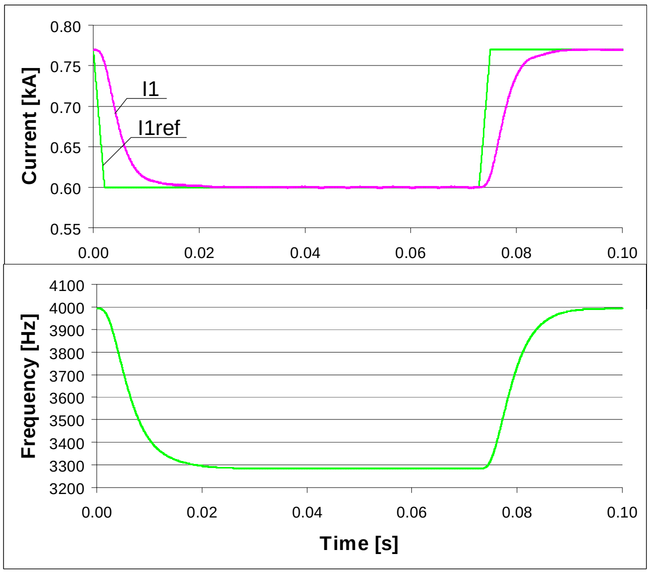

Figure 6. Converter response for a step in current reference.

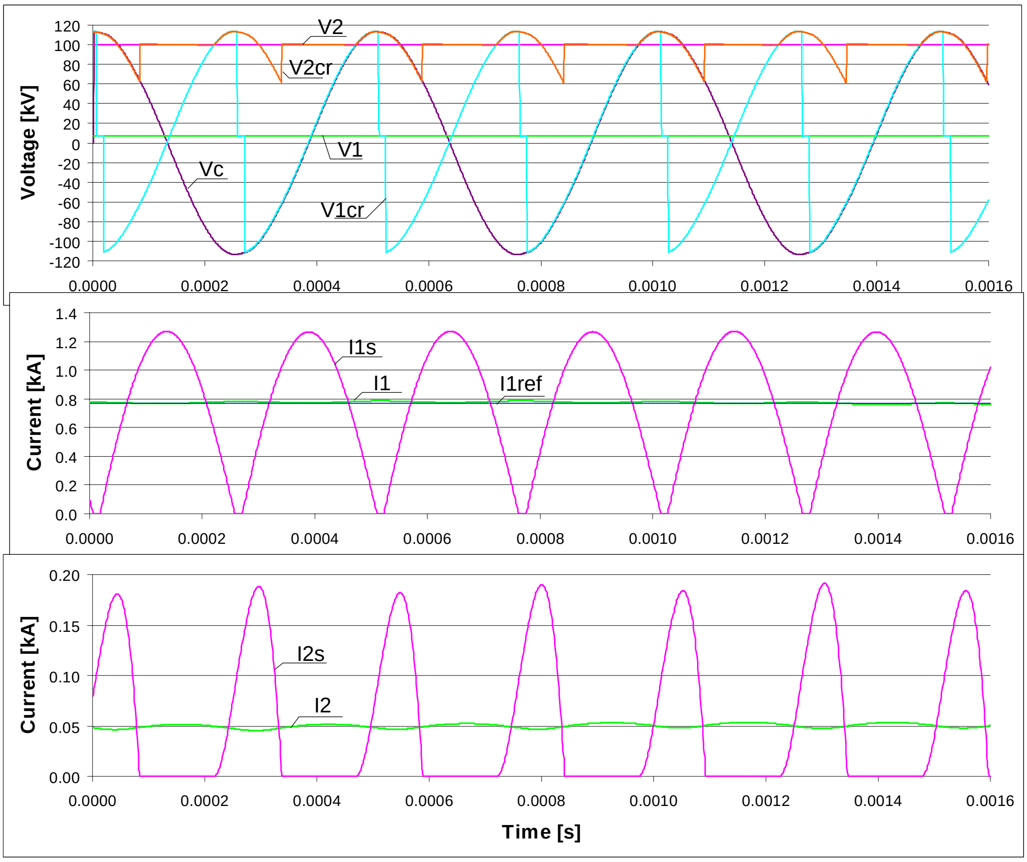

Figure 7. Steady-state converter variables at *5MW* power transfer.

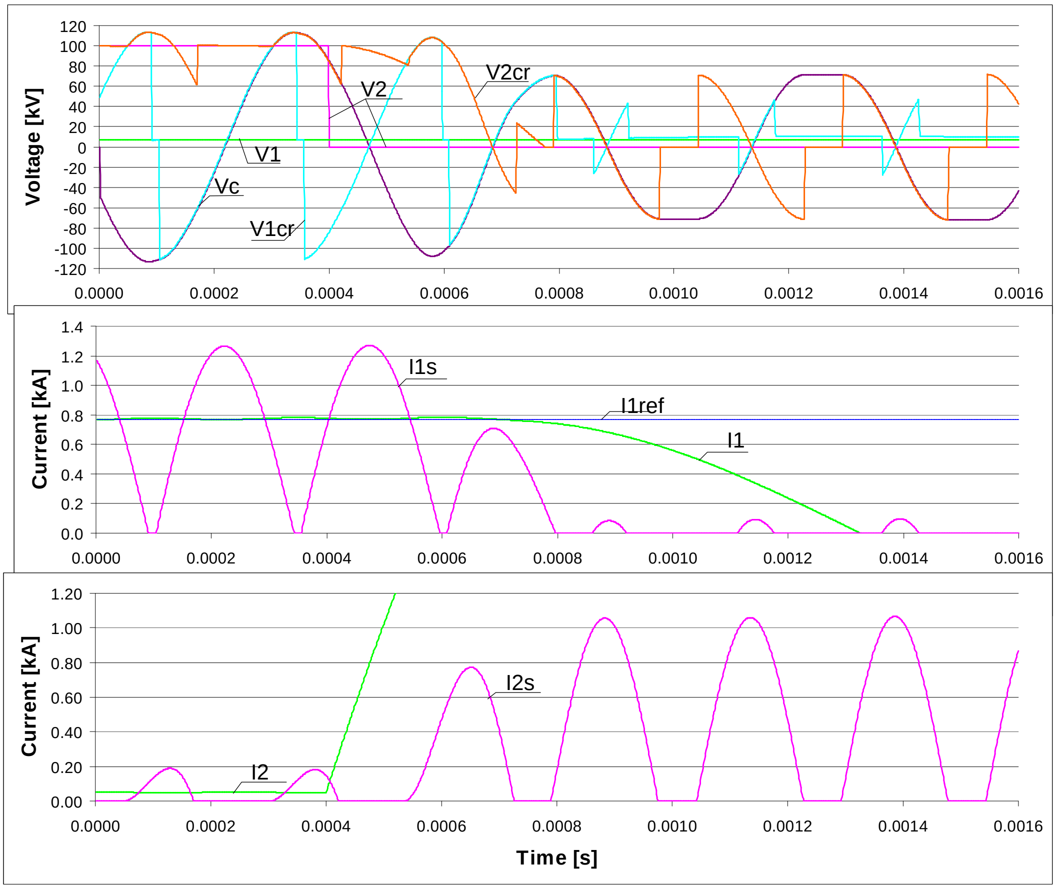

Figure 8. Simulation responses for a fault at terminal $V_2$. .

### B. *Fault conditions*

The faults on low voltage side ($V_1$) are not critical and they will only result in interruption of power transfer. The faults on the high voltage side ($V_2$) have potential for shoot-through and can propagate fault current to the low voltage side. However tests show that using thyristors in high voltage circuit and with sufficiently high $L_2$ the converter can maintain normal operation even under most severe ($V_2=0$) faults.

Figure 8 shows the responses for a severe fault at high voltage terminals with the considered test converter. It is seen that the converter does not experience commutation failure during the fault. Furthermore, the converter naturally reduces the current on the unfaulted side ($I_1$) and therefore it does not propagate the fault.

It is noted that filters in general have negative influence on the fault responses. In order to prevent large overvoltages an antiparallel diode is used across the filter capacitor $C_{f2}$.

## V. CONCLUSIONS

This paper presents detailed design of a high-power resonant DC/DC converter for application with an offshore wind farm. The simulation results confirm that a *5MW 6.8kV/100kV* converter is feasible with reasonable size and losses.

It is concluded that inverter-grade thyristors might be optimal switches because they enable operation at higher switching frequencies. The operation at *4kHz* switching frequency implies that the weight of the largest inductor is around *610kg*. The overall efficiency for the test converter is expected to be around *96-97%*.

The detailed simulation results demonstrate that the converter has very good fault tolerance. In order to provide complete tolerance to high-voltage faults it is required to use controllable switches (thyristors) and to employ a sufficiently high inductor in the high-voltage circuit.

## VI. APPENDIX TESTS SYSTEM

TABLE A.1 TEST CONVERTER PARAMETERS

| *parameter* | *value* | | *parameter* | *value* |
|---|---|---|---|---|
| $f_s$ *[Hz]* | *4000* | | $L_1$ *[mH] (x2)* | *3.3* |
| $V_1$ *[kV]* | *6.8* | | $L_2$ *[mH] (x2)* | *2* |
| $V_2$ *[kV]* | *100* | | $C_{f1}$ *[μF] (x2)* | *150* |
| $I_{1av}$ *[A]* | *770* | | $L_{f1}$ *[mH] (x2)* | *1* |
| $I_{2av}$ *[A]* | *50* | | $C_{f2}$ *[μF] (x2)* | *10* |
| $V_{cmax}$ *[kV]* | *113* | | $L_{f2}$ *[mH] (x2)* | *5* |
| $C_r$ *[μF] (x2)* | *1.8* | | | |

## VII. ACKNOWLEDGEMENTS

The Authors are thankful for the financial support from the Royal Academy UK, and National Research Council Canada.

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## IX. BIOGRAPHY

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