DTU Library

Comparative study of hybrid synchronous condenser incorporating battery energy storage system for ancillary service provision

Nuhic, Mirza; Kkuni, Kanakesh Vatta; Yang, Guangya; Ramachandran, Jayaraman

Published in:
Proceedings of 19th Wind Integration Workshop

Publication date:
2020

Document Version
Peer reviewed version

Comparative study of hybrid synchronous condenser incorporating battery energy storage system for ancillary service provision

Mirza Nuhic, Kanakesh Vatta Kkuni and Guangya Yang
Department of Electrical Engineering
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
Email: *mirnuh@elektro.dtu.dk*

Jay Ramachandran
National Grid ESO
Email: *jay.ramachandran@nationalgrideso.com*

Abstract*—In the face of the increasing penetration of renewable energy sources, the synchronous machine-based power plants are slowly being phased out. This fact is potentially creating severe system issues in the transmission network. Key among the problems faced are the reduction of short circuit levels, inertia, as well as steady-state and dynamic reactive power support. To enhance the transmission system power transfer capability, complementary technological solutions, including synchronous machines, energy Storage Systems, and reactive power compensation devices can be combined to provide more services than a single device. Phoenix project, funded by Ofgem through Network Innovation Programme, is deploying a hybrid synchronous condenser (H-SC), which is a hybrid system of synchronous condenser (SC) and static synchronous compensator (STATCOM), and at the same time looking at the option of combining SC and battery energy storage system (BESS). In order to maximize the benefits of the hybridization of SC and BESS, there remains a need to assess and quantify the grid support functionalities provided by the SC and BESS individually, as well as a part of a hybrid solution. Furthermore, the control of the BESS converter solution to mimic the synchronous machine termed as grid-forming control is also drawing significant interest from the recent years owing to the potential of improved grid response characteristic compared to the grid supporting controls using phase-locked loop (PLL) and DQ current control. In this paper, we analyse the grid support functionalities provided by the SC, BESS with grid-forming and grid-following control, separately as well as a part of a hybrid system with synchronous condenser.

I. Introduction

Decommissioning of synchronous machine-based power plants is creating challenges to the power system related to inertia, voltage stability, and short circuit power levels. The ever increasing penetration of solar and wind power is interfaced by power converters, which inherently do not possess the capabilities of a synchronous machines, such as inertia support, significant overloading capability in terms of dynamic voltage support, and high short circuit current contribution. Furthermore, the cascaded control loops in power converters can pose a serious challenge in terms of system stability.

In recent years, we have seen an increase in synchronous condenser installation in order to address the issues related to decrease of synchronous machine-based generation [1]. An attractive solution for industry is a hybrid synchronous condenser system consisting of a synchronous condenser and static compensator (STATCOM). Scottish Power and Energy Network initiated a pilot project where a hybrid SC is installed at Neilston substation in Scotland, UK [2], and commissioned in 2020. The system is connected to the 275 kV transmission network with a rating of 140 MVA. It is characterized by a coordinated control of the two technologies by the master controller, which includes voltage control and reactive power sharing, improved fast transient response, power loss minimization, among others [3]. The frequency support is very limited as STATCOM cannot provide active power, so the system's active power contribution relies solely on the inertia of the synchronous condenser. In [4], a similar hybrid system from the Phoenix project is proposed consisting of a synchronous condenser and a battery energy storage system (BESS). The converter is controlled in grid support mode to provide conventional droop control for the active and reactive power. The control consists of cascaded outer and inner loop, as well as a basic phase-locked loop (PLL) for grid synchronization. Multiple control loops and the PLL dynamics can possibly have a negative impact on the response and stability of the converter. A significant improvement on this type of control strategy is a power-synchronization based control where the need for PLL and additional control loops is avoided by implementing a simple control concept using the phase angle and voltage magnitude to directly control the active and reactive power [5]. Main disadvantage of this control strategy is that it requires an additional control at current limit in case of severe grid disturbances. Once the current limit of the converter is reached, the control must switch to current control mode and additionally, a PLL is required. Power-synchronization control can be categorized as virtual synchronous machine (VSM) type of control and converters equipped with this control strategy are known as grid-forming converters (GFC). In [6], the authors investigate the capability of the GFC connected at the onshore PCC of the offshore wind farm as opposed to synchronous condenser and STATCOM.

There has not been study in literature that provides detailed assessment of the characteristics of different hybrid solutions in terms of technologies and controls. Therefore, the focus of this paper is to investigate and compare the capabilities of the different technologies and control strategies and attempt to quantify the contribution in terms of voltage and frequency support. The criteria for comparison are based on the speed of the response, overloading capability, and performance in weak and strong grids. The idea is to test each technology and control strategy against voltage and frequency disturbance, voltage angle jump, and short circuit. The rest of the paper is organized as follows. In section II, a general overview of the different technologies and their capabilities is provided. Section III contains the description of the test system, the simulation results and discussion on the findings. Finally, in section IV, a brief conclusion is provided.

II. Components and Control Models

A. Technology Comparison

There is a notable difference in how the synchronous machine and power converter operate, both in terms of control and in terms of their capabilities. One of the main advantages of synchronous condensers over power converters is the significant overloading capability and short-circuit contribution. Synchronous condenser can provide up to 3.5 pu of rated current during faults, while the power converters are limited by design for up to 1.3 pu of rated current. The short circuit level of the system has a significant influence on voltage levels and protection operation during faults. Furthermore, synchronous machine have rotating masses and this means that the inertia is an inherent feature of synchronous condenser, which is an especially important factor for future systems with high penetration of renewable energy. Power converters, on the other hand, provide fast frequency support (if coupled with active power source), fast voltage control, and the possibility of a number of different control strategy implementations. Synchronous condenser has much slower response to voltage reference change and voltage dips in comparison with power converters and since there is no prime mover the only contribution in terms of active power is inertia. Additional advantage for power converters is the capability to provide full rated current in inductive and capacitive mode. In terms of control strategies, power converters can be divided in grid-following and grid-forming converters. The two main advantages of grid-forming converters are the save of the otherwise used cascaded control loops and PLL and provides faster voltage and frequency support, while the main drawback is switching to current control in case of current exceeding the maximum limits.

Based on the characteristics of the individual technologies, some general assumptions on the performance of the combined effect of the individual technologies considered as a single hybrid system can be made as shown in Table I. The hybrid system is assumed to be of the same total rating as the individual components. This will effect some of the characteristics of the SC and the power converter response. The main advantages of a hybrid system over a synchronous condenser are the extended range of frequency support, increased rating of reactive current, storing electric energy, compensating for slower voltage regulation of the SC, and maximization of the inertia support to the system by compensating for the SC oscillations. The advantages of the hybrid system over BESS are: inertia support, increased

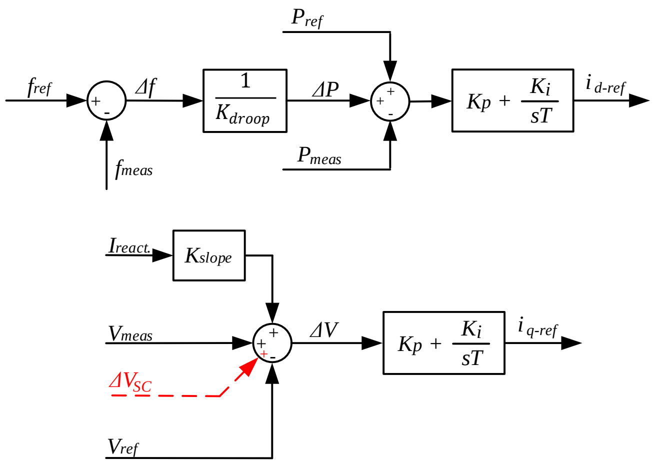

Fig. 1. Grid-Following Control

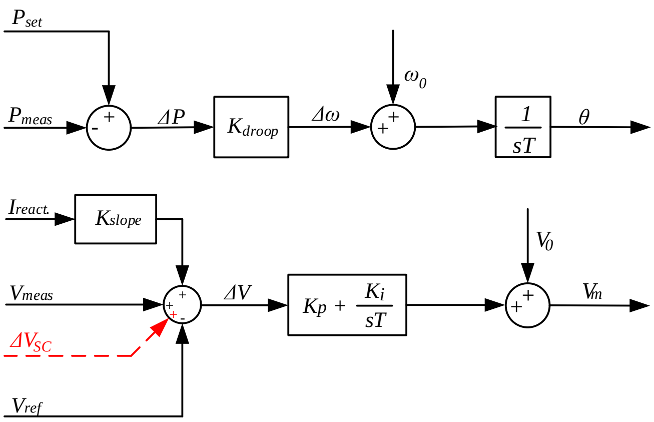

Fig. 2. Grid-Forming Control

overloading capability, and increased short-circuit current contribution. The obvious drawback of the hybrid system is that we are effectively reducing the contribution from the SC as the rating of the machine is two times lower. The study in this paper compares the benefits and limitations between different technologies and try to draw conclusions on the design and application in different situations.

B. Control Modelling

BESS model is based on the work done in [4], where the battery is modelled as equivalent circuit of two RC networks and voltage controlled voltage source. Synchronous condenser is a standard synchronous machine operating without a prime mover. SC is controlled by the AVR model based on the standard IEEE AC8B AVR model. The grid-following converter control is based on the standard *dq* domain control with outer and inner control loops. The inner (current) control is a well known standard model with *dq* decoupling and feed-forward voltage. The reference currents are generated in the outer loop as shown in figure 1. The d axis current-control loop controls the active power and consequently provides frequency support in a form of droop control, while the q axis-control loop controls the reactive power and provides voltage support and ensures equal reactive power sharing between the SC and BESS (they have the same K_{slope} parameter). The grid-forming

TABLE I
TECHNOLOGY COMPARISON

Technology	Inertia/Fast Freq. Response	Volt./Curr. Characteristic	Short-Circuit Current	Response Time
SynCon	1.3 - 3.5 s typical values for the inertia constant* Instantaneous Response	High overloading capability Physical limitations for the inductive mode, close to 0.5 pu of rated current	3 - 3.5 pu of the rated current at subtransient time scale**	Seconds for post-fault settling time and reference voltage change
BESS Grid Following	No inertia Droop control Possibility of so-called synthetic inertia	Full rated reactive current for cap. and ind. mode Possible instability due to cascaded control loops and PLL	Constrained by the overcurrent limiter, typical values 1.1 - 1.3 pu	1 - 3 cycles
BESS Grid Forming	No inertia Fast freq. response, similar to SM Possibility of so-called synthetic inertia	Full rated reactive current for cap. and ind. mode	Constrained by the overcurrent limiter, typical values 1.1 - 1.3 pu Requires current control once the current exceeds max. value	0.5 - 2 cycles
SynCon + BESS Grid Following	1.3 - 3.5 s inertia constant* Instantaneous Response + droop control Possibility of so-called synthetic inertia	High overloading capability Less than 1 pu of inductive current due to the SynCon limitations (close to 0.75 pu) Possible instability due to cascaded control loops and PLL for BESS	2.05 - 2.4 pu of the rated current at subtransient time scale**	Improved response for post-fault settling time and reference voltage change due to the compensation of SynCon by BESS
SynCon + BESS Grid Forming	1.3 - 3.5 s inertia constant* Instantaneous Response + fast freq. response, similar to SM Possibility of so-called synthetic inertia	High overloading capability Less than 1 pu of inductive current due to the SynCon's limitations (close to 0.75 pu)	2.05 - 2.4 pu of the rated current at subtransient time scale** BESS requires current control once the current exceeds max. value	Improved response for post-fault settling time and reference voltage change due to the compensation of SynCon by BESS

*Depends on the design of the machine, can be higher, **Depends on the design of the machine, can be higher

converter control is based on the power synchronization control as demonstrated in [5]. As can be seen in figure 2, the error between the measured and reference active power is transformed to a frequency deviation, By integrating the frequency, the voltage angle reference is obtained and the use of PLL is unnecessary. The power synchronization control implemented here is equivalent in structure to the inertia less virtual synchronous machine control termed VSM0H [6]. The reactive power loop is very similar to the grid-following control and the difference is that the output of the loop is the voltage magnitude. The signal marked with red (ΔV_{SC}) is the voltage feedback signal from the SC. The response of the SC for sudden changes in the voltage, and post fault recovery is relatively slow, so by adding the SC voltage error (this is the same voltage delta ΔV as in the converter control) we can compensate that lag by providing more reactive power from the converter, as described in [3].

III. SIMULATION AND RESULTS

The test system used for simulating the different technologies is a simple system where the grid is represented by an equivalent generator for frequency response scenario (as shown in Fig. 3), while for the other scenarios, we used a Thevenin equivalent. The generator is rated at 24 kV / 2.2 GVA connected to the grid through a transformer, while the Thevenin voltage source is connected directly to the 275 kV rated grid. The hybrid system is connected to the grid through a three-winding transformer. The rating of the synchronous condenser and the power converer is the same at 70 MVA in the case of the hybrid system, while the individual technologies are rated at 140 MVA in order to ensure consistent capacity and comparable results. The droop settings for both the voltage and the frequency control are set to 5%. The inertia constant of the synchronous condenser is 1.35 seconds.

A. Frequency Event Scenario

The performance level in terms of frequency support is evaluated in a system as shown in Fig. 3 where a load of 330MW is switched on at 1 second. Two scenarios have been evaluated where the inertia constant of the grid equivalent generator was 3 seconds for the first test, and 4 seconds for the second test. The frequency of the system for the two scenarios is shown in Fig. 4 and Fig. 5. As expected, the response of BESS operating as grid-following and grid-forming is very similar after the first 200-300 milliseconds. The grid-following converter is slower to respond to the frequency change because of the additional control loops and mainly because of the PLL. The contribution of SC is limited to inertial support, so the only differentiating factor between the hybrid system and the individual BESS technology in terms of frequency nadir and steady-state frequency is the rating of the component. A notable difference in the response

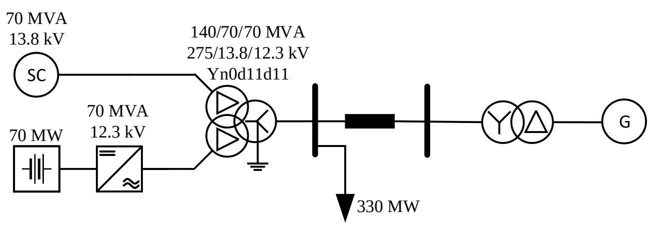

Fig. 3. Test System Including the Grid Equivalent

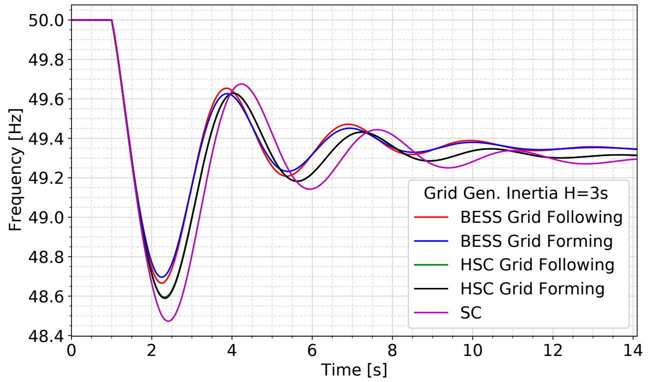

Fig. 4. Frequency Response - 3s inertia constant

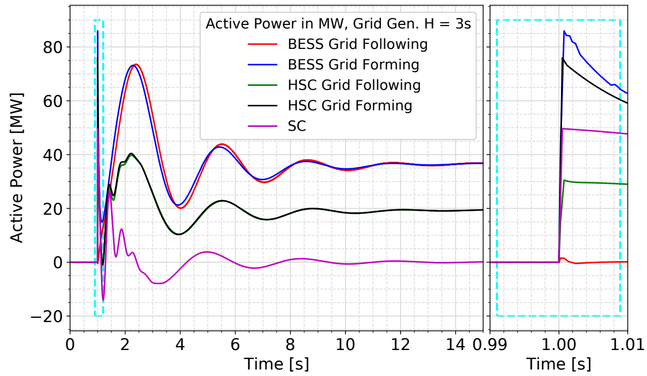

Fig. 6. Active Power Contribution - 3s inertia constant

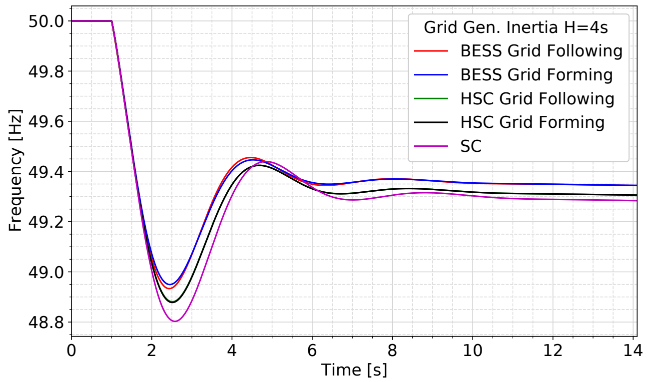

Fig. 5. Frequency Response - 4s inertia constant

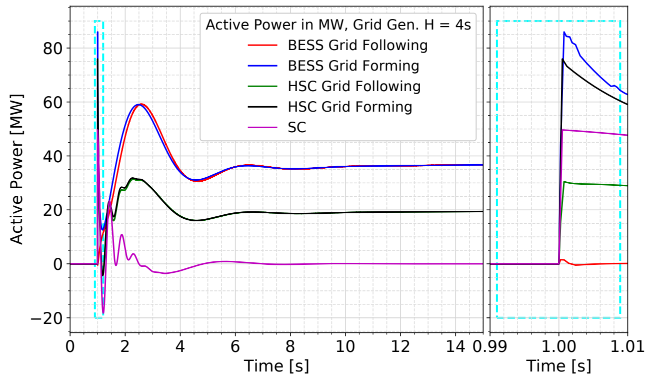

Fig. 7. Active Power Contribution - 4s inertia constant

of each technology is within the first 200-300 milliseconds as can be seen in Fig. 6 and Fig. 7. The peak active power injection instantly following the load step from the grid-forming BESS is 85MW, while for the grid-forming hybrid system the peak power is 75MW. The synchronous condenser peak contribution is 50MW. The grid-following hybrid system peak active power injection is 30MW, which is a contribution from the synchronous condenser, while grid-following BESS does not provide a notable contribution initially as the controller is based on the droop control.

B. Voltage Phase Jump Scenario

For this scenario, we have a grid represented by a Thevenin equivalent with two levels of short circuit power representing the weak and strong grid at 500 MVA and 2800 MVA, respectively. The voltage phase change of +30 degrees is applied at 1 second. The voltage phase tracking by each of the technology is shown in Fig. 8. The grid-following BESS provides no significant active power contribution for weak and strong grid scenario as seen in Fig. 9. The grid-following hybrid system contribution is mostly from the synchronous condenser. The grid-forming BESS provides the response superior to other systems as it provides the highest level of response to the voltage phase disturbance. In the case of a strong grid, the grid-forming BESS and hybrid system hit the current limitation and switch to current control mode for a short period, resulting in a prolonged settling time. This efect is due to the reduced impedance between the Thevenin source and the system under investigation.

C. System Voltage Drop

As in the previous scenario, the grid is represented by a Thevenin equivalent. At 1 second, the system voltage instantaneously changes to 0.5 pu. For a weak system (SCL = 500 MVA), the reactive current injection from the converter and the synchronous condenser results in a significant voltage retention as the Thevenin impedance is relatively high, as shown in Fig. 10, left. The grid-following and grid-forming BESS are current limited to 1.2 pu, so the contribution from the converter is the same pu value in all cases (Fig. 11). For the weak grid case, the voltage settles at 0.84 pu with the converter solution, while for the hybrid system and synchonous condenser solution the voltage is approximately 0.9 pu following the disturbance. The retained voltage is higher in the latter case due to the overloading capability of the synchronous condenser. The same disturbance in a strong grid (Fig. 10, right) results in a lower voltage as the Thevenin impedance is significantly lower than in the previous case. The voltage is at approximately 0.56 pu for grid-forming and grid-following BESS, 0.59 pu for the HSC solutions, and 0.61 pu for the synchronous condenser system. The difference between the HSC and SC solutions is due to the fact that the SC has a rating of 140 MVA, while the SC in the hybrid system is rated at 70 MVA and consequently the hybrid system provides less reactive current as the converter is current limited to 1.2 pu, as shown in Fig. 11. The grid-forming based solution provides the faster response in comparison to the grid-following solution as the grid-forming converter control does not contain the current

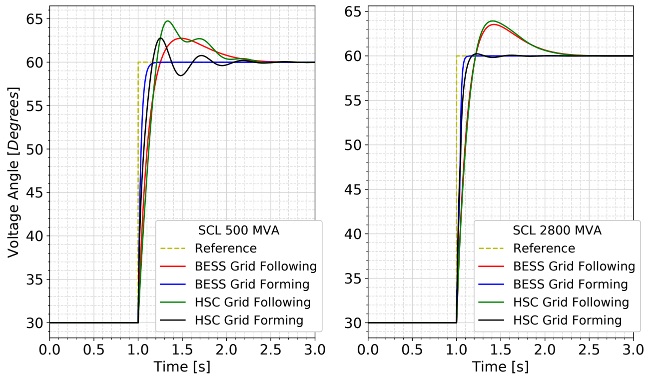

Fig. 8. Grid Voltage Phase Jump by 30 Degrees: Left - 500MVA SCL, Right - 2800MVA SCL

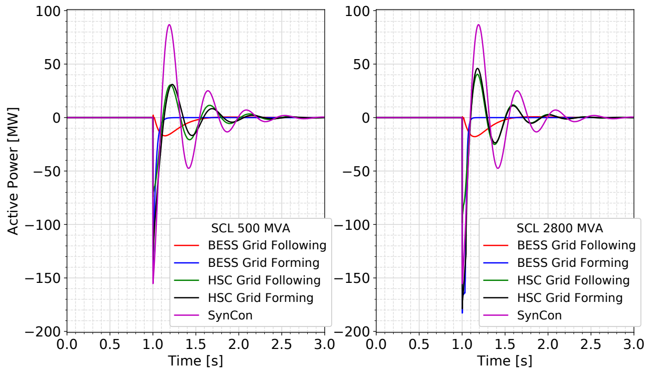

Fig. 9. Active Power During Voltage Phase Jump: Left - 500MVA SCL, Right - 2800MVA SCL

control loop and the PLL.

D. Short-Circuit Scenario

The three-phase short circuit is applied at 1 seconds at the PCC bus of the system. The short-circuit is a three-phase to ground fault with a fault resistance of 5Ω and a duration of 200 milliseconds. The voltage at the PCC for the weak grid is close to 0.045pu as the contribution from the grid is limited due to high impedance (500MVA SCL), and 0.18pu for the stronger grid, as shown in Fig. 12. SC shows the typical synchronous machine response during short circuits with current peak being at the initialisation stage of the fault when the subtransient reactance is dominant. The SC contributes with a current of 3 pu for the weak grid scenario (Fig. 13, left), and 2.9 pu for the stronger grid (Fig. 13, right). The difference in current contribution is due to the voltage at PCC being lower for the weak grid scenario. Contribution from the converter is predictably flat, reaching the current limit of 1.2pu and staying constant. The total contribution from the HSC solution is 2.41 pu for the weak grid, and 2.36 pu for the strong grid. The difference between the grid-forming and the grid-following solution is not significant during the fault, the grid-forming converter being slightly faster to reach the peak value. Post-fault, the synchronous condenser introduces active power oscillations and significant reactive power swing. By using the voltage compensation technique described previously, this reactive power injection from the SC can be significantly reduced in the case of the hybrid system, where most of the power can be absorbed by the

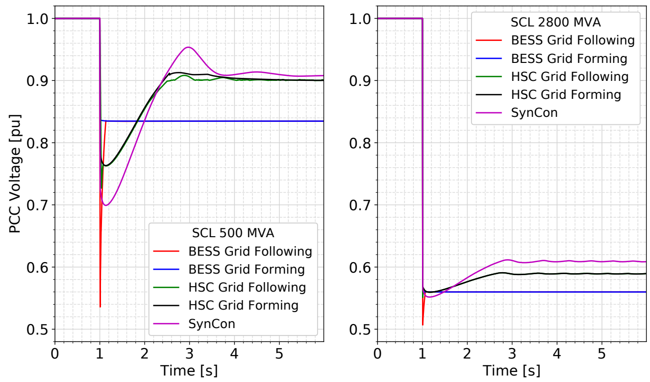

Fig. 10. Voltage at PCC for 0.5pu System Voltage Drop: Left - 500MVA SCL, Right - 2800MVA

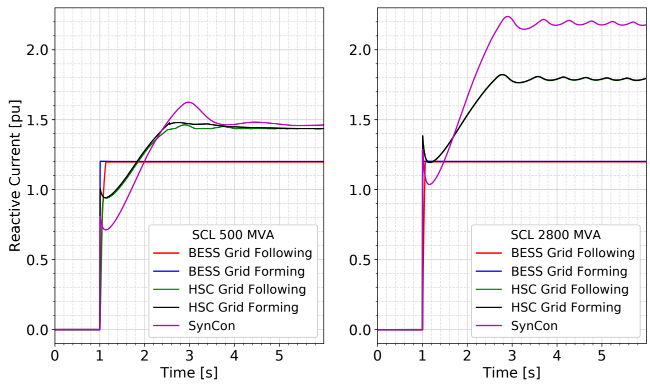

Fig. 11. Reactive Current Injected at PCC for 0.5pu System Voltage Drop: Left - 500MVA SCL, Right - 2800MVA

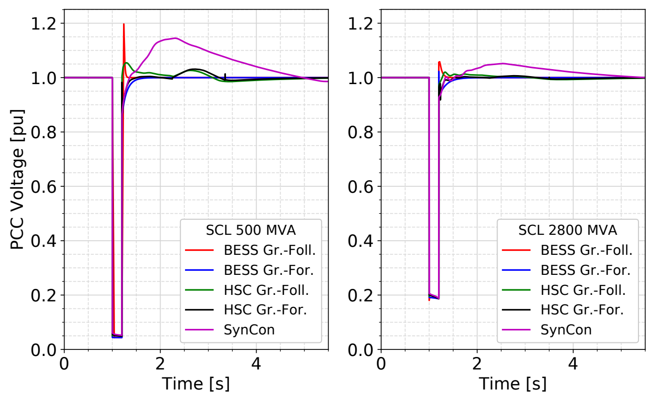

Fig. 12. Voltage at PCC During Short-Circuit: Left - 500MVA SCL, Right - 2800MVA SCL

converter, and thus reduce reactive power exchange with the grid.

IV. Conclusion

A summary of the performance of the technologies considered in the paper against the test cases in Section III is shown in Table II. The instantaneous response measured at the half-cycle period, and the dynamic response, which is assessed based on the technology's response quality, are ranked from best to worst. The Syncon adds more robustness due to its notable overload capability, whereas the converter's current limiters can introduce a discrete response to large transients.

TABLE II
SUMMARY OF THE TEST CASE WITH PERFORMANCE OF EACH TECHNOLOGY RANKED FROM BEST TO WORST (1-5)

Technology	**Frequency Event**		**Voltage Phase Jump**		**System Voltage Drop**		**Short-Circuit Event**	
	Instantaneous	Dynamic	Instantaneous	Dynamic	Instantaneous	Dynamic	Instantaneous	Dynamic
SynCon	3	5	1	3	4	1	1	2
BESS Grid Following	5	4	5	5	5	5	5	5
BESS Grid Forming	1	1	3	1	1	4	4	4
SynCon + BESS Grid Following	4	3	4	4	3	3	3	3
SynCon + BESS Grid Forming	2	2	2	2	2	2	2	1

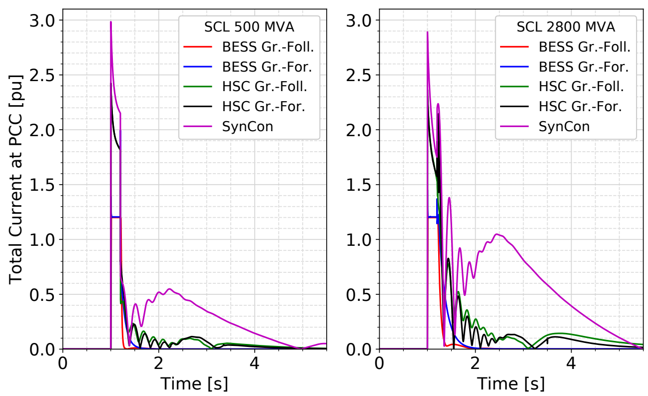

Fig. 13. Current Magnitude Injected at PCC During Short-Circuit: Left - 500MVA SCL, Right - 2800MVA SCL

The grid-forming converter based solutions provide the most balanced response in terms of frequency support as they provide very fast response and in many ways are similar to the synchronous machine. In terms of voltage support, the solutions with synchronous condenser are dominant due to the significant overloading capability of the SC. The slower SC response can be compensated by faster converter control, which gives an advantage to the hybrid solution. Similarly, for short-circuit events, the solutions with synchronous condenser provide the best solution in terms of short-circuit current contribution, while the converter based solutions provide balanced post-fault response. Based on the findings in this work, we can conclude that the hybrid concept with grid-forming control brings the most balanced performance overall for grid support.

ACKNOWLEDGMENT

The study is funded by Phoenix project, funded by Ofgem under Network Innovation Competition programme, Project Direction ref: SPT / Phoenix / 16 December 2016 (https://www.spenergynetworks.co.uk/pages/phoenix.aspx).

REFERENCES

[1] Phoenix project, international review. (2019). [Online]. Available: https://www.spenergynetworks.co.uk/userfiles/file/Phoenix_-_International_Project_Review.pdf

[2] Phoenix project. (2020). [Online]. Available: https://www.spenergynetworks.co.uk/pages/phoenix.aspx

[3] R. Rivas, A. Owens, F. Wang, E. Arnsten, R. Rui, and C. Foote, “Phoenix: The world’s first hybrid synchronous condenser system,” in *CIGRE Session 48, Paris*, 2020.

[4] M. Nuhic and G. Yang, “A hybrid system consisting of synchronous condenser and battery - enhanced services for weak systems,” in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, pp. 1–5, 2019.

[5] L. Zhang, L. Harnefors, and H. Nee, “Power-synchronization control of grid-connected voltage-source converters,” *IEEE Transactions on Power Systems*, vol. 25, no. 2, pp. 809–820, 2010.

[6] M. Yu, R. Ierna, A. Dyśko, A. Egea-Àlvarez, A. Avras, C. Li, M. Horley, C. Booth, H. Urdal *et al.*, “Performance of hybrid power park technologies in future ofto networks with the aim to achieve grid-forming capability,” in *19th Wind Integration Workshop*, 2019.