Enhancing the Grid Compliance of Wind Farms by Means of Hybrid SVC

P. Vuorenpää, *Student Member, IEEE*, and P. Järventausta

***Abstract*--Despite reactive power control capability of the modern wind turbine generator units have almost reached the capability of the traditional generator units the applied wind farm configuration can result insufficient reactive power capability in the point of common coupling. For instance, when utilizing AC grid connection, long electrical distance from the main grid or possible high charging current of the offshore sea cable usually require additional compensation capacity in the cable ends to ensure proper voltage profile of the farm and meet the Grid Code requirements set by the utility.**

In this paper dynamic compensation scheme, called Hybrid SVC, is presented to improve the reactive power control capability and thereby feasible grid connection of wind farms with AC grid connection. In addition, fast controllability of the Hybrid SVC unit may also improve the response of the wind farm in case of low voltage conditions. After discussing the benefits of dynamic compensation in connection of wind farm application in general, possible benefits of Hybrid SVC based dynamic compensation in case of medium size offshore wind farm is demonstrated in PSS/E and RTDS environments. It is concluded, that a Hybrid SVC device with proper ratings could improve the feasible grid connection of wind farm and enable decreased ratings for the wind turbine generator units.

***Index Terms*—Wind farm, Grid Code, Hybrid SVC, SVC, STATCOM**

I. Introduction

IN the future, locating wind farms on far away from the main grid is assumed to gain more interest due to possible higher capacity value of wind power and decreased environmental effects. At the same time though, long electrical distance from the main require careful assessment on designing the grid connection system between the wind turbine generator units and the point of common coupling to minimize the transmission losses and to fulfill the grid connection requirements. Despite the possible benefits of DC grid connection of wind farms AC grid connection can still be considered as the most economical solution in case of medium size wind farm application. [1] However, reactive power management with additional reactive power compensation is usually required to enable feasible grid connection. Reactive power management of wind farms can include e.g. utilization of the reactive power control capability of the wind turbine generators, on-load tap changers of the transformers, mechanically-switched shunt reactors and capacitors or dynamic compensation devices such as Static Var Compensator (SVC) or Static Synchronous Condenser (STATCOM). [2, 3]

Various studies have proven the effectiveness of SVC and STATCOM based compensation approaches in improving the grid compliance of the wind farm applications. [4, 5, 6] Whereas STATCOM based compensation approach provides fast response times and nominal current injection capability independently from the prevailing voltage level SVC with same ratings can be considered to have both lower investment and operational costs due to decreased switching losses. Therefore, a dynamic compensation device, referred as a Hybrid SVC, combining the benefits of both SVC and STATCOM device could be seen a cost effective alternative in specific application areas. In [7] benefits of a scheme of this kind were studied in connection of an arc furnace application. Based on the promising results of the previous studies, in this paper the analysis is extended to cover also the special characteristics of wind farm applications.

The target of the paper is to discuss and analyze the potential and benefits of Hybrid SVC based compensation scheme with different configurations in ensuring the feasible grid connection of a medium size offshore wind farm. The main interest of the paper is to evaluate the contribution of Hybrid SVC device in reactive power control capability of the wind farm in normal operation conditions and reactive current injection capability in case of low voltage conditions. Finally, real time simulation configuration and results from the simulations related to Hybrid SVC device with real control implementations of the both SVC and STATCOM parts of the device is presented and analyzed briefly.

II. Reactive Power Compensation of Wind Farms

A. Reactive Power Compensation Requirements of Wind Farms

In general, in some countries the penetration level of wind energy based electricity generation and at the same time the capacity of individual wind farms connected to common connection point has increased rapidly in recent years. This has also enforced the utility to take these new distributed generation units more actively into account, when determining

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the interconnection requirements for these new generation plants. As a common objective for most of the existing Grid Code requirements concerning wind farms is to require similar steady-state and dynamical control characteristics for the wind farms as is required from any traditional power plant with same ratings. However, strong variability in the available wind energy as well as the special characteristics of the wind turbine generator (WTG) units and the farm configurations can complicate the fulfillment of the most restricting requirements. In addition, the fact that usually the optimal locations for new wind farms are far away from the nearest connection point to the main grid can result high impedances between the Point of Common Coupling (PCC) and the generation unit and therefore make it harder to comply with the present-day Grid Code requirements.

1) Required Reactive Power Capacity

In most of the Grid Code requirements WTG units capable of active voltage control are required to participate in voltage control of the PCC in a specified reactive power range. In Fig. 1 few examples of the required reactive power ranges for the WTG units are presented. [8]

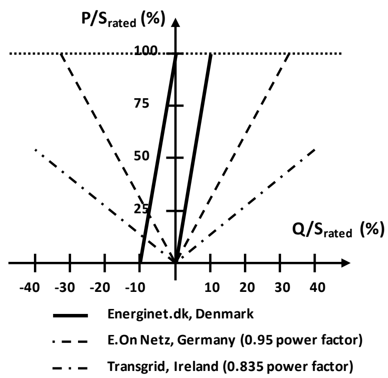


Fig. 1. Examples of different reactive power requirements of the utilities [8]

Despite the operational range of modern WTG units equipped with power converters usually covers the required reactive power control range, in some cases their ability to participate in voltage control at the PCC may be limited due to the long electrical distance to the PCC.

2) Reactive Current Injection Requirements

As another example of present day Grid Code requirements E.On. Netz Grid Code [9] specifies the required reactive current capacity of the WTG unit as a function of the voltage drop. (Fig. 2)

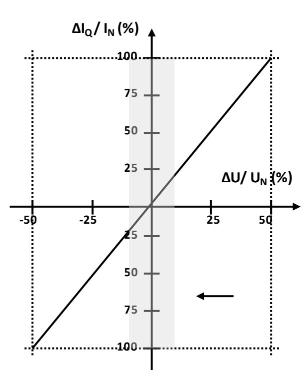


Fig. 2. Reactive current injection requirement of E.On Netz Grid Code [9]

After a specific dead band in vicinity of the nominal voltage reactive current injection capability of 2 times the voltage change in p.u. is required. Moreover, the required reactive current injection is required in 20 ms after the voltage change has been observed. Basically, many of the modern WTG units can be equipped with additional reactive current injection capability of this kind, but it usually means additional stresses on both electrical and mechanical systems of the unit and thereby results over sizing of the WTG units. [10]

B. Alternatives for Reactive Power Compensation

In general, effective reactive power compensation of wind farms can be considered to have two main objectives:

- to maintain the voltage profile of the wind farm at appropriate level and thereby ensure minimum losses in transferring the generated electrical energy to the main grid
- to fulfill the grid connection requirements related to reactive power compensation characteristics set by the local utility.

There exist several alternatives to manage the reactive power balance of the wind farm and at the same time provide the desired reactive power capacity at the PCC. [2, 3] In the end, decision of the applied reactive power compensation techniques will rely on extensive feasibility studies taking into account both technical and economical considerations.

On-load tap changers of the step-up transformers can be applied to maintain the voltage level of the WTG bus in specific level, which can be seen beneficial e.g. in operating the WTG units close to their nominal voltage or in controlling the reactive power generation of the shunt connected reactive power sources of the wind farm configuration. In addition, mechanically switched capacitive and/or inductive elements can be applied effectively in case of varying network conditions. However, as a downside of the switchable reactive power capacity is usually the lack of continuous controllability and possible switching transients related to the switching events. However, e.g. regulated reactors are introduced to enable smoother control of the inductive reactive power capacity of the system. [2, 3] Furthermore, in case of AC cable based transmission solutions the cable itself can provide a substantial capacitive reactive power source to be utilized in reactive power balancing of the wind farm configuration.

Introduction of the variable speed WTG units, such as doubly-fed induction generators (DFIG) and full converter wind turbine generators (FCWT), has enhanced the control capabilities of the WTG units significantly compared to the WTG units operating with fixed speed ratio. Consequently, due to the controllable converter technology of the WTG units, modern WTGs are capable of controlling their reactive power output in a range specified by the component ratings of the unit. In Fig. 3 an example of possible PQ characteristics of a DFIG based WTG unit is presented. [11] However, it should be noted that even though Fig. 3 indicates reactive power generation capability even with zero real power generation, in practice, the WTG units of the wind farm will most likely be disconnected from the grid in no-load conditions resulting both zero real and reactive power generation for the wind farm.

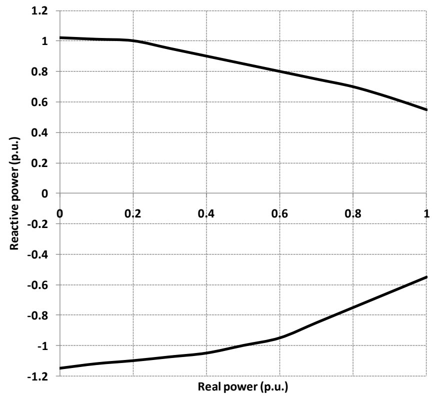


Fig. 3. Possible PQ characteristics for DFIG based WTG [11]

In addition to reactive power compensation alternatives presented above, Flexible AC Transmission Systems (FACTS) based compensation devices, such Static Var Compensator (SVC) or Static Synchronous Compensator (STATCOM), can provide a feasible and continuously controllable alternative for reactive power compensation purposes of wind farm applications. In addition to the steady state reactive power compensation, due to their fast controllability, FACTS devices can also be applied effectively in case of transient phenomena to improve the overall stability of the system. So far, despite their superior performance compared to other reactive compensation alternatives, the relatively high investment costs of such devices have slowed down the utilization. In the paper reactive power compensation alternatives related to FACTS devices are referred as dynamic compensation.

III. Dynamic compensation and Hybrid SVC in Wind Farm Application

A. Benefits of Dynamic Compensation in Case of Wind Farm Application

In general, it should be noted that interests of the wind farm owner and the utility towards investing to dynamic compensation solutions can be strongly related to the distribution of the costs and benefits gained from the applied technology. However, few of the main benefits of applying dynamic compensation in case of wind farm applications are listed below.

1) Compensation capacity is independent of the wind conditions

Reactive power control limits of wind turbine generator capable of operating within a specific power factor range are basically more or less related to the prevailing wind conditions. On the contrary, reactive power control capability of the dynamic compensation device can be basically considered independent of the prevailing wind conditions. This ability can be seen to benefit especially the utility, which has to maintain the reactive power balance of the system regardless of the prevailing wind conditions. However, in the future also the wind farm owner could gain additional profits from the dynamic compensation investment by providing the reactive power control capacity for the use of the utility in cases, where the WTG units are not operating.

2) Could enable decreased rating of the wind turbine generators

Utilization of dynamic compensation device in connection of wind farm application basically increases the total reactive power control capability of the wind farm and thereby could enable operation of the WTG units with decreased power factor. Moreover, under low voltage conditions dynamic compensation device with STATCOM related characteristics can take part in injecting reactive current into the PCC and thereby decrease the reactive current injection requirements of the WTG units.

3) Controllable reactive power capacity can be located in vicinity of the PCC

Transferring significant amounts of reactive power generated by the WTG units to the PCC increases the overall losses of the wind farm. Thereby, locating controllable reactive power capacity in vicinity of the PCC could be seen an economical alternative especially with increasing length of the grid connection.

4) Decrease the number of switching operations of other compensation devices

Compared to switchable compensation capacity, dynamic compensation alternatives offer continuous control of the reactive power capacity without discrete switching events possibly resulting transients in the system. Consequently, dynamic compensation devices can also decrease the control events of transformers with on-load tap changers.

B. Hybrid SVC Concept

The main idea behind the Hybrid SVC concept presented in the paper is basically to combine partly scaled SVC and STATCOM devices into a single unit, which current injection capability and response times are superior compared to a pure SVC device but at the same time the investment costs and losses are less than the ones of a pure STATCOM device with same rating. To illustrate the improved current injection capability of such unit the VI-curve of Hybrid SVC with 25 % of STATCOM and 75 % of SVC is presented in Fig. 4.

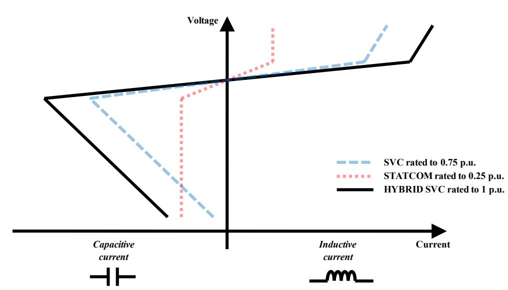


Fig. 4. VI-curves for SVC, STATCOM and Hybrid SVC applications

In Fig. 5 the main configuration of the Hybrid SVC scheme is presented. After step-down transformer from 150 kV to 20 kV SVC bus includes Thyristor Controlled Reactor (TCR) and filters to the lowest harmonic components. In addition, the filter branches can also provide specific amount of capacitive reactive power and thereby enable operation of the SVC unit in both inductive and capacitive operation regions. In addition, STATCOM part of the Hybrid SVC device is connected through a separate connection transformer (20 kV/2 kV), which transforms the voltage of the SVC bus to more appropriate level regarding the operation range of the IGBT switches. Operation range of the STATCOM part of the Hybrid SVC device is limited by the rated current of the IGBT switches.

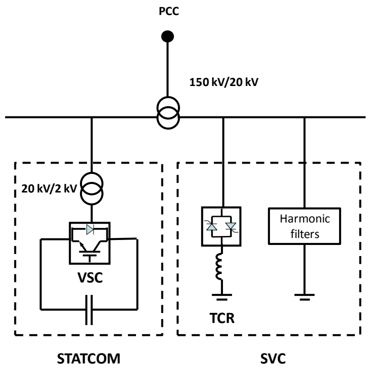


Fig. 5. Single-line diagram of the studied Hybrid SVC configuration

IV. Studied System Configuration

Similar system configuration was modeled in both PSS/E and RTDS environments. Operation of the Hybrid SVC based compensation scheme was demonstrated in case of aggregated medium size offshore wind farm (~100 MVA) with AC grid connection (~50 km). (Fig. 6) Cable connection from the WTG units to the mainland introduced a significant capacitive component, which had to be compensated with additional shunt reactances (~80 %). In addition, short overhead transmission line (OHL) was included in the model to represent the connection of the offshore sea cable to the PCC, which was located at the onshore substation. Detailed parameters of the studied system configuration are presented in Appendix.

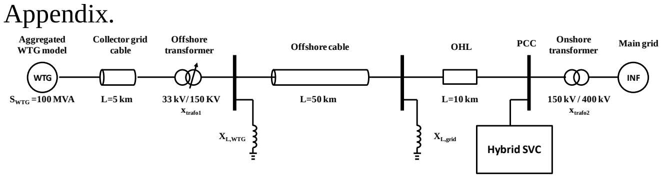


Fig. 6. Single line diagram of the studied system configuration

In the paper the PCC is considered as the connection point for the Hybrid SVC device because it basically enables more effective utilization of the compensation capacity of the device from network point of view. Moreover, the PCC is usually situated in vicinity of the mainland and offers therefore economical savings in terms of lower maintenance costs.

To illustrate the limited reactive power control capability of the WTG units in case of offshore wind farm implementation reactive power control range of the wind farm measured at the PCC is presented in Fig. 7. The aggregated WTG unit was operating according to PQ-curve of Fig. 3 and the terminal voltage of the unit was limited from 0.9 p.u to 1.1 p.u. and the Hybrid SVC was disconnected from the system.

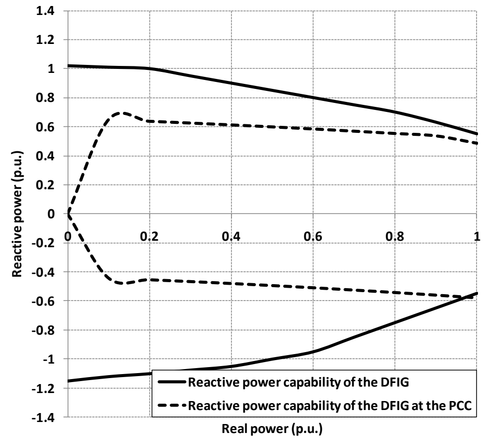


Fig. 7. Reactive power capability of the DFIG at the PCC

Based on the results presented in Fig. 7 it can be concluded that in case of the studied system configuration the terminal voltage actually becomes the most dominant factor limiting the reactive power control capability of the farm. Thereby, it seems evident that additional reactive power compensation capacity should be considered to balance the voltage profile of the wind farm and enable operation of the wind farm at optimal voltage level.

V. Enhancing the Grid Compliance of Offshore Wind Farm by Means of Hybrid SVC

A. Meeting the Reactive Power Requirement at the PCC

Two different example configurations of Hybrid SVC based compensation in case of offshore wind farm is presented in the paper. In the first example configuration WTG units are operated with unity power factor and the required reactive power range (example of the existing Grid Code requirements in [8]) is covered completely by the Hybrid SVC device located in vicinity of the PCC. In the second example configuration WTG units are enabled to operate in reactive power range from -20 MVars to 20 MVars and thereafter rest of the required compensation capacity is covered by the Hybrid SVC. Resulted reactive power capability of the wind farm in these two example configurations are presented in Fig. 8 and Fig. 9.

In both cases the control coordination between the reactive power controllers are executed in a way that the capacity of the STATCOM part is utilized last. In this way the fastest compensation capacity could be reserved to be used e.g. in case of sudden voltage drops in the system.

It should be noticed that the demonstration were executed with nominal system voltage level and full real power injection of the WTG units for convenience. Basically, low system voltage and high real power generation of the WTG units would, to some extent, increase the inductive reactive power capability of the wind farm whereas high system voltage and low real power generation of the WTG units would increase the capacitive reactive power capability.

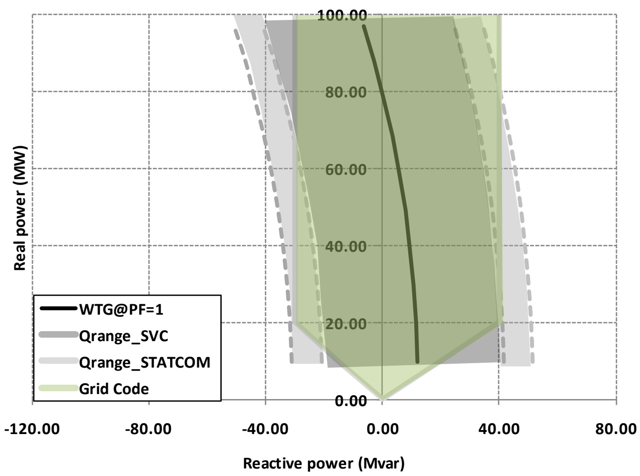


Fig. 8. Reactive power capability of wind farm with Hybrid SVC (PF_{WTG}=1, ±0.4 p.u. Hybrid SVC unit with 25 %/75 % division rate)

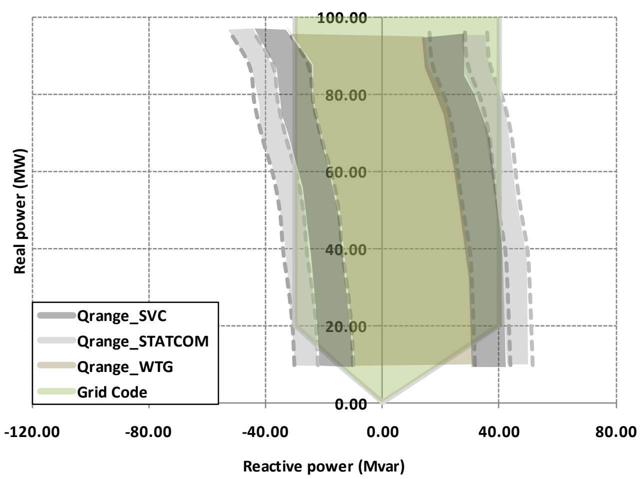


Fig. 9. Reactive power capability of wind farm with Hybrid SVC (Q_{WTG}= -20 MVar to 20 MVar, ±0.4 p.u. Hybrid SVC unit with 25 %/75 % division rate)

B. Improving the Reactive Current Injection Capability of Wind Farm

More commonly the Grid Code specifications related to the grid connection of WTG units to the transmission network requires also specific reactive current injection capability and response times for the wind farm in case of low voltage conditions. [9] Thereafter, studies have also proven that the response of the modern WTG units can be configured to comply even with the tightest requirements related to the reactive current injection capability. [10, 12] However, in some cases it could result in significant stresses for the electrical and/or mechanical components and overrating of the WTG units and thereby to higher expenses for the whole wind farm investment. In contrast to this, capacity of the dynamic compensation device could be utilized to increase the reactive current injection capability of the wind farm and thereby result lower stresses for the WTG units.

In case of Hybrid SVC based dynamic compensation the reactive current injection capability of the device is a sum of the individual SVC and STATCOM units. Based on Fig. 4 the current injection capability of the STATCOM unit is basically independent of the terminal voltage whereas the current injection capability of the SVC unit decreases linearly respect to the decreasing terminal voltage. Consequently, current injection capability of the Hybrid SVC unit can be estimated analytically by taking into account these well known relations.

Assuming reactive current injection capability $i_{q,\mathrm{WTG}}$ for the WTG units (corresponding the capability curve presented in Fig. 3) and denoting the reactive current injection capabilities of the SVC and STATCOM units as $i_{q,\mathrm{SVC}}$ and $i_{q,\mathrm{STATCOM}}$, respectively, the increased current injection capability by applying Hybrid SVC device can be denoted as Δi_q. In Fig. 10 a) and b) the theoretical current injection capabilities of the wind farm with different Hybrid SVC configurations are presented.

$$i_{q,SVC} = \frac{Q_{SVC,cap} \cdot (1 - u_{dip})}{S_{WTG}} \quad (1)$$

$$i_{q,STATCOM} = \frac{Q_{STATCOM}}{S_{WTG}} \quad (2)$$

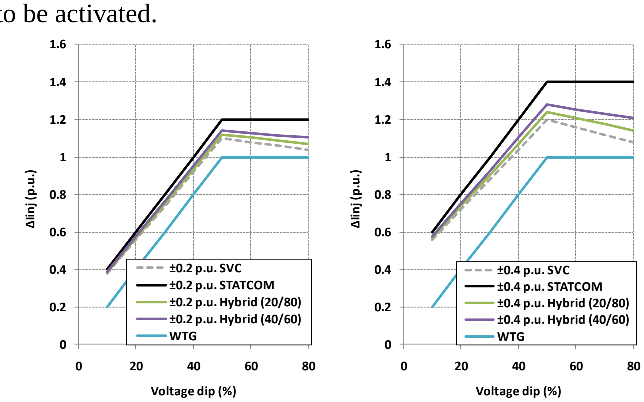
$$i_{q,Hybrid} = i_{q,SVC} + i_{q,STATCOM} \quad (3)$$

$$i_{q,WTG} = 2 \cdot u_{dip} \quad (4)$$

$$(\textit{based on Grid Code requirement})$$

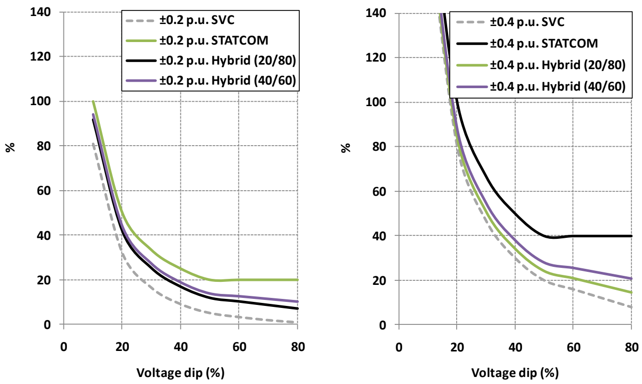
$$\Delta i_q = \frac{i_{q,Hybrid}}{i_{q,WTG}} \quad (5)$$

Moreover, from Fig. 11 it can be observed that the current injection capability of the wind farm can be increased up to 30 % in case of 50 % voltage dip by applying Hybrid SVC based compensation (±0.4 p.u. Hybrid SVC (40/60)). Basically this means that the current injection capability of the wind turbine generators could be decreased approximately by 30 % without losing the compliance with the examined Grid Code requirement. Similarly, in case of smaller voltage dips the reactive current injection requirement could be meet completely with the Hybrid SVC unit and in these cases low voltage logics of the wind turbine generators would not need to be activated.



a) b)

Fig. 10. Reactive current injection capability of wind farm with and without Hybrid SVC



a) b)

Fig. 11. Relative increase in reactive current injection capability of wind farm with Hybrid SVC

VI. Real Time Laboratory Simulations of Hybrid SVC and DFIG Based Wind Farm

RTDS simulation environment offers practical means to execute Hardware-in-Loop (HIL) simulations in real-time basis. [13] Thereby, behavior of the actual power system can be emulated in laboratory environment and characteristics of the studied power system components can be developed and tested in a realistic and effective manner without a connection to the real power system.

In addition to the theoretical analysis and studies executed with PSSE power flow program RTDS based real-time simulation environment was utilized to develop an actual control implementation for the Hybrid SVC based compensation application. In following the applied system configuration and example of the executed simulation studies are presented.

A. Real Time Simulation Configuration

Laboratory set up of the Hybrid SVC device consisted of the real control hardware of the independent SVC and STATCOM units and power system model representing an offshore wind farm with aggregated DFIG based WTG unit. (Fig. 6) However, due to the fact that the power rating of the STATCOM controller was fixed to ±2 MVar’s and only one controller unit was available at the time of the simulations, also the parameters of rest of the power system model had to be downscaled to attain realistic scaling between the studied power system components. Thereupon, the studied system configuration consisted of DFIG based wind farm configuration rated to 20 MW’s and SVC model rated to ±6 MVar’s resulting a ±0.4 p.u. Hybrid SVC unit with 25 %/75 % division rate calculated in wind farm base. Consequently, the parameters presented in Table I. were downscaled with ratio of 1 to 5.

The default solution time step in the RTDS simulation environment is 50 μs, which usually can be considered sufficient e.g. in case of most of the common power system components. However, due to the high switching frequency of the Voltage Source Converter (VSC) technology, which was applied both in DFIG and STATCOM models of the studied system configuration small time step modeling with solution time step of 2 μs was utilized to determine the switching instants for the IGBT bridges of these two models more accurately.

B. Low Voltage Ride Through of Wind Farm with Hybrid SVC

To illustrate the operation and response characteristics of the real time system configuration related to Hybrid SVC implementation response of the system to sudden voltage drop is presented in Fig. 12. In the presented situation voltage of the PCC drops suddenly approximately to 0.5 p.u. of the nominal due to fault in the main grid. During the fault of 200 ms controllers of both SVC and STATCOM units react immediately to the voltage drop by injecting maximum capacitive reactive current to the PCC. Whereas response time of the STATCOM controller is inherently in range of only few 2 ms, response of the SVC unit can also be speed up by blocking the firing pulses to the thyristors right after the reduction of the measured voltage below a specific threshold value. Thereafter, compensation capacity of the SVC unit equals directly the capacitive reactance of the filter branches. As a conclusion, the current injection capability of the Hybrid SVC implementation corresponded well with the analytical results presented in Chapter V and the response time is, as expected, well beyond the limits set by the example Grid Code. [9]

As can be observed from Fig. b), the applied aggregated DFIG model did not include any additional low voltage logics, which would have contributed to the reactive current injection capability of the DFIG. Consequently, both real and reactive power generation of the WTG decreased due to the dip in the terminal voltage. Moreover, the overvoltage protection of the DC circuit was realized with chopper circuit, which managed to maintain the voltage of the DC circuit in appropriate level. Crowbar protection of the rotor side converter was not included in the applied model, which could result over currents in the rotor side converter in specific circumstances. In the future, more accurate modeling of the low voltage logics and protection measures of the DFIG model should be included to give more insight to the overall low voltage ride through capabilities of the studied wind farm configuration. However, despite these shortages, the executed simulation cases could still be considered to give realistic insight to the response characteristics of the Hybrid SVC implementation in case of low voltage conditions and be utilized in further development related e.g. to the control coordination between the controllers of the SVC, STATCOM and WTG units.

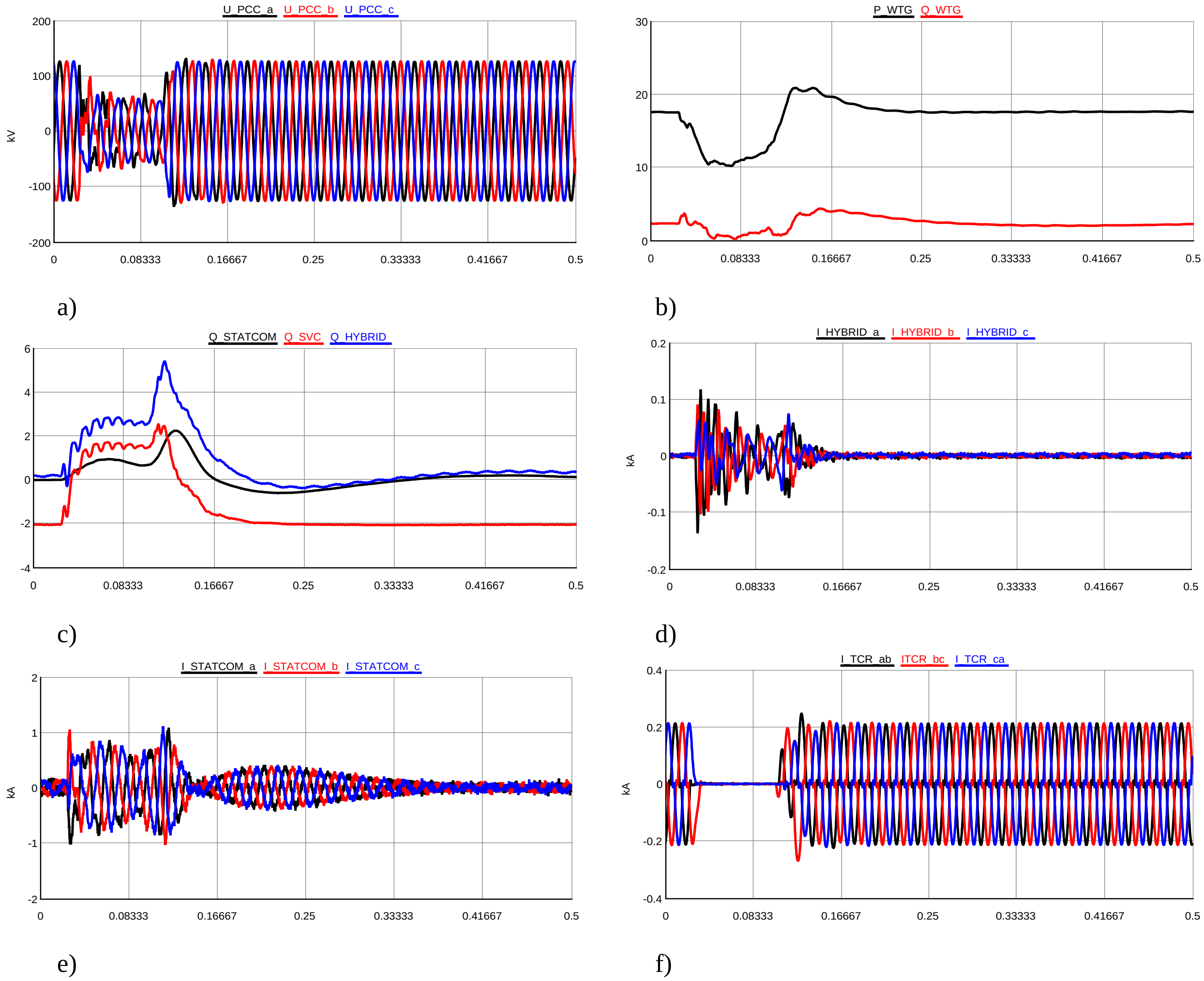


Fig. 12. Response of the real-time Hybrid SVC implementation and DFIG wind farm to sudden voltage drop in the system
a) Voltage of the PCC ($U_{nom,L\text{-}L}$=150 kV)
b) Real and reactive power of the wind farm
c) Reactive powers of the SVC, STATCOM and Hybrid SVC
d) Current of the Hybrid SVC ($U_{nom,L\text{-}L}$=150 kV)
e) Current of the STATCOM ($U_{nom,L\text{-}L}$=2 kV)
f) Current of the TCR branch ($U_{nom,L\text{-}L}$=20 kV)

VII. Conclusions

In the paper potential and feasibility of the Hybrid SVC based dynamic compensation scheme in case of wind farm applications was evaluated from theoretical and technical point of views. As a conclusion, based on the preliminary studies executed in the paper dynamic compensation with Hybrid SVC based solution may in some cases found to be a respectable alternative to meet the existing Grid Code requirements of a specific wind farm configuration. In other words, the Hybrid SVC scheme can increase both reactive power and reactive current injection capability of the wind farm and thereby improve the grid compliance of wind farm configuration. However, the comprehensive feasibility study concerning the most applicable compensation solutions for a specific situation can be considered to be highly sensitive to applied prices for e.g. the electrical components, losses and component ratings. Therefore, further studies related to the overall feasibility of the Hybrid SVC based compensation scheme taking into account the economical point of view should be executed.

VIII. Appendix

Table I. Applied system parameters

S_{WTG}	100 MVA
$r_{collector\_cable}$	0.04 Ω/km
$x_{L,collector\_cable}$	0.11 Ω/km
$x_{C,collector\_cable}$	0.28 µF/km
S_{trafo1}	170 MVA
x_{trafo1}	10 %
$r_{offshore\_cable}$	0.04 Ω/km
$x_{L,offshore\_cable}$	0.12 Ω/km
$x_{C,offshore\_cable}$	0.20 µF/km
$x_{L,WTG}$	1125 Ω
$x_{L,grid}$	1125 Ω
r_{OHL}	0.03 Ω/km
$x_{L,OHL}$	0.12 Ω/km
$x_{C,OHL}$	0.01 µF/km
S_{trafo2}	170 MVA
x_{trafo2}	10 %
$S_{SCC,main\_grid}$	5000 MVA

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