Optimization Modeling for Offshore Wind Farms

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***Abstract*— Offshore wind farms have emerged as the biggest contributor of renewable energy to the national grid over the last decade, driven by advanced technology, higher investment, and lowering operational and maintenance costs. This demonstrates the value of improving the efficiency in wind farms, with designs to be selected for the most effective transmission system implementation.**

This paper describes the simulation models developed with network simulation software (IPSA and PowerWorld) for evaluating and analyzing the load flow by observing the losses, voltage magnitude and transmitted power, both active and reactive. There were three different models, one using standard inter-array cable (33 kV) and one with upgrade inter-array cable to 52 kV. The third model proposed replacing high voltage side transformers with a mechanically switched capacitor (MSC) rather than the usual static Var compensator.

Results from 52 kV models revealed that high voltage cable in offshore wind farms is capable of transmitting more active power than medium voltage. Indeed, the losses in this design are in the range of theoretical value in between 0.3% and 11%. The MSC losses agreed using a value of 1.7%. the results of the third model showed that static Var produced more active power than mechanically switched capacitor. At the same time, the static Var produced the highest reactive power at export cable. Although the static Var models have performed better than mechanically switched capacitors, in terms of monetary value mechanically switched capacitors are better than static Var compensators. The parameters of the design were given by Siemens, where their supplier confirmed that initial costs including operation and maintenance cost for mechanically switched capacitor are lower compared to the transformer.

Keywords—Offshore wind farm, 52 kV, mechanically switched capacitor, static Var compensator.

I. Introduction

The rapid development of wind power globally has led to increased focus on wind energy in many countries [1]. The global scale of wind energy grew by $24.8 billion reflecting an increase of 35% from 2010 to 2018 [2]. As reported by [2], wind power in offshore is gaining prominence and demonstrates a steady state rise over 11 years from 2019 onwards relative to other renewable sources. Offshore wind power currently accounts for 4.26% of global cumulative capacity. Wind power plants have been seen as a crucial element of sustainable energy policies, meeting green-house gas emissions goals and enhancing future power stability [3]. Today, several countries across the world are anticipated to develop higher rates of penetration as renewable energy is considered a safe, clean, sustainable alternative to traditional energy sources, and a stimulating economic choice in locations with sufficient wind resource. In other ways, the integration of high wind power penetration rates (>30%) across huge international, integrated electrical systems entail a step by step restructuring of the current electrical system and operation strategies. Indeed, it is more likely to be a financial problem rather a technical one. This integration of substantial wind power penetration rates is not only feasible but does not necessitate a lot of restructure of the current power grid. A designer of a wind plant must balance the benefit gained from reduced losses, and imposed availability against the corresponding cost of capital required to achieve such improvements [4].

This paper aims to compare three different methods of taking wind generation from offshore Wind Farms to onshore grid connection using network modelling software to indicate the effect on power quality and losses of each system. This will inform the developer of the wind farm as to the most efficient way to transmit the generated power.

II. Reactive Power Compensation

A Reactive Power Compensation (RPC) device is required to reduce the reactive power in order to enhance the efficiency of network power systems. Besides that, it also improves the stability of the system by raising the maximum active power which could be transferred to the transmission system [5]. Capacitors and inductor (or reactors) are static devices because they have no active control of the reactive power output in response to the system voltage. They just supply and consume static reactive power. Meanwhile, Flexible AC Transmission Systems (FACTS) including static Var compensators (SVC) and static compensators (STATCOM) are categories of dynamic reactive power devices. They have the capability to change their output based on pre-set limits in response to the changing system voltages. [6].

A. Mechanically Switched Capacitor

Mechanically Switched Capacitor (MSC) is the most economical RPC device with simple design low speed resolution for voltage control and grid stabilization under heavy load conditions. They have little or no effect on short-circuit power, but they increase the voltage at the point of connection [7]. MSC is helpful for voltage stability by allowing the local generator to operate close to unity power factor. As a result, it maximizes fast acting reactive reserve [8]. The advantage of MSCs is that they can improve the performance, quality and efficiency of electrical systems, minimize power losses, improve the cost effective system, improve the power factor of the line, increase the active power transmission capacity and transient stability margin, attain effective voltage control and damp power oscillation [9]. MSC switching is limited to 2,000 – 5,000 cycles before the switch must be changed, limiting the use of the MSC because the required level of reactive power (var) compensation changes gradually. As MSC has lower losses, they preferred applications that consistently require capacitive injection [10].

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B. Static Var Compensator

SVC is one of the FACTS equipment composed of a reactor component with a large set of inductive RPCs and a capacitor both as a source and as a switching device. It is a generator/load connected shunt static Var in which the output is set for the exchange of inductive or capacitive currents for the retention or control of the power system [11]. The SVC runs soft electronic switching of its own shunt reactors and/or capacitors to achieve continuous reactive power variation. Particularly suited for controlling the varying demand for reactive power of large fluctuating loads and overvoltage characteristics due to load rejection [12]. The SVC can be operated in two modes: Voltage regulation mode (voltage regulation is limited) and VAr control mode (the SVC susceptance is kept constant). The V-I characteristic shown in Figure 1 is applied in voltage regulation mode. This characteristic represents the steady state relationship and the range of inductive and capacitive current supplied by the SVC [13]. Figure 1 highlights that as long as the SVC susceptance B remains within maximum and minimum susceptance values, imposed by the total reactive power of the capacitor banks (Bc_{max}) and reactor banks (BI_{max}) the voltage is regulated by the reference voltage V_{ref}. Indeed, the voltage drop is normally used (between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in Figure 1.

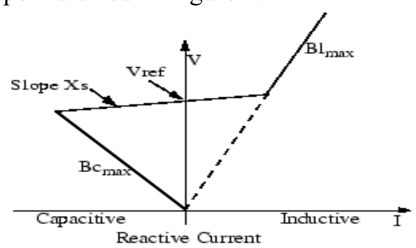

Fig. 1. SVC V-I characteristics.

III. Higher Voltage Inter Array Cable (66 kV)

The trend towards larger and more efficient wind turbines requires a specific cabling array. The higher voltage 66 kV cables and associated connections enable the traditional offshore configuration to be retained compared to 33 kV, with strings of four to five or even more wind turbines positioned in a row [14].

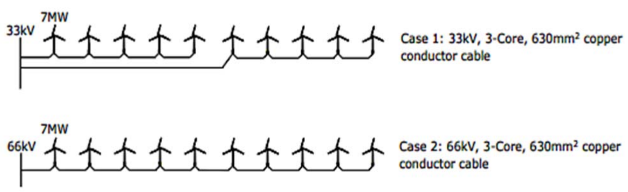

Fig. 2. Collection array system with cable 33kV and 66kV.

The operating voltage of the array cable system is a key area for conceptual design consideration [15]. In Figure 2 case 1 where the array system voltage is operating at 33 kV, approximately 40 MW of power is transmitted using a 630 mm^2 copper conductor cable. However, the same cross section cable is able to transport around 80 MW when operating at the 66 kV array system voltage in case 2. It can be concluded that, rather than having two array cables, only one would be required to transport the same level of power in the 66 kV case. The benefit of using one circuit over two to transmit the same level of power is that, 66 kV alternative may be required for a given amount of cable, but this depends on the design of the wind farm. The illustration shown in Figure 2 assesses the potential for removal of one-third of the 33 kV array cable quantity. When the number of cables is fewer, there is a potential reduction in the initial costs over the 33 kV option. A higher voltage inter-array system can decrease the number of cable strings entering the platform as more wind turbines can be connected per string, reduced system losses, reduce total cable length, increased efficiency with smaller cross-section and lower current, and therefore do not require extra transformer substations. This will generate significant cost savings with lower life cycle costs and intra-array cable layout optimization, which will drive more power to the future offshore wind farm design [16], [14].

IV. Modelling and Simulation of the Models

The load flow study was conducted using two network modeling software packages; IPSA and PowerWorld. Both these packages use Newton-Raphson iterative methods to calculate the busbar voltages and power flows in the network. There were three models designed for this study. Figure 3 shows the basic structure of the models designed for the research.

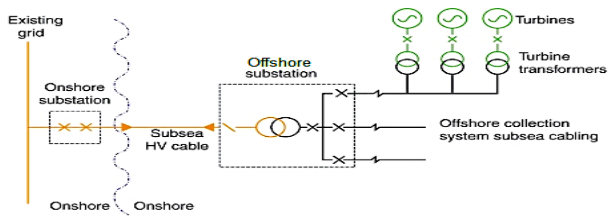

Fig. 3. Basic structure of wind farm model.

The network design is as follows; see Fig 4 for arrangement Bus 1 is the slack bus where the wind farm connects to the Grid, bus 2 is the step-up transformer to transmission line and bus 4 is the step down to 33 kV. Points 6 and 3 are where the cable size changes on the HV line. The cable values are based on those given by Siemens. For all parameter data and per-unit values in the models, refer to Appendix (Table II – V). The values found at the per unit voltage on the busbar and the real and reactive power flow on the connectors.

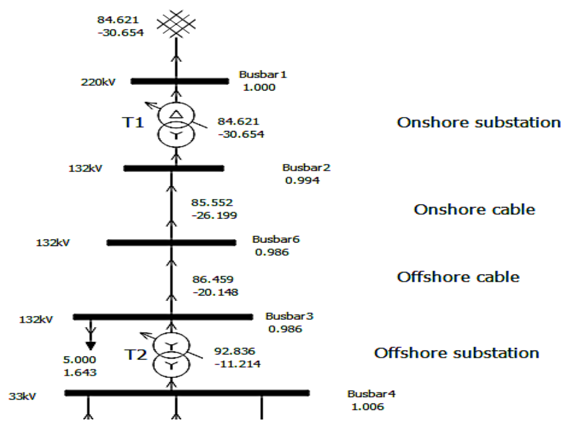

Fig. 4. Network arrangement from grid to Busbar 4

A. Model 1: Cable versus RPC Devices (MSC and SVC) Using 33kV Inter Array

Figure 5 shows the model simulated without RPC devices. While Figure 6 and 7 shows models with MSC and SVC, respectively. Note that the number of 33 kV array cables was reduced from 5 to 2.

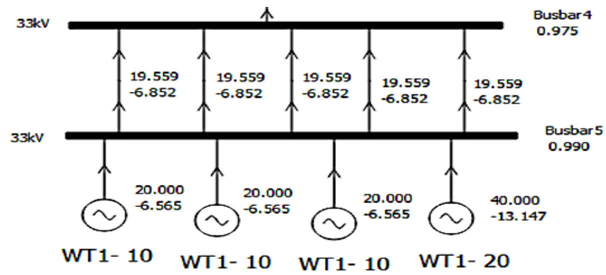

Fig. 5. Model 1.1: 33 kV and 5 inter-array cables

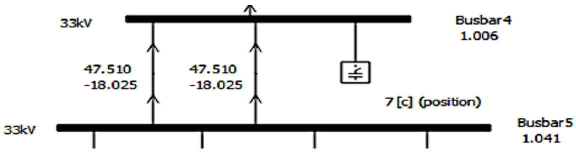

Fig. 6. Model 1.2: MSC device

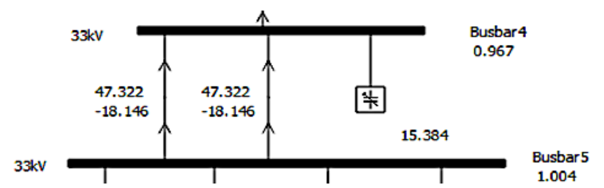

Fig. 7. Model 1.2: SVC device

1) The Busbar Voltage

The voltage is recorded at each busbar for the three systems. The comparison is shown in Fig. 8.

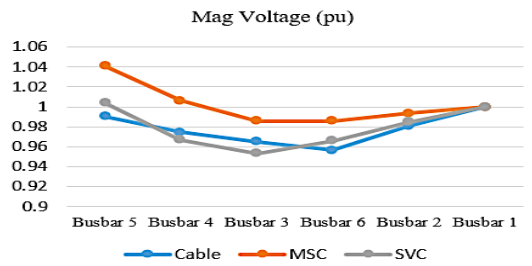

Fig. 8. Bus voltage for Model 1

From Busbar 5 (turbine connection) the bus voltage gradually decreased to busbar 3 for MSC and SVC design and then increased slightly to busbar 1 (slack), whereas for the cable layout, it began to rise after busbar 6. The highest, stable voltage occurred in the MSC model, because it increases the voltage at each point of the connection and improved the losses on the transmission. Between busbar 4 and busbar 6, MSC's capacitor banks stabilised the reduction loss voltage in the system. In the case of SVC its role is to control and stabilise the voltage in the transmission network. SVC can provide instantaneous control of temporary voltages but they have limited capacity for overload. The issue with cable usage is the reactive power produced in the cable, which seems to be a consequence of the capacitance between phase conductor and the earth. The power losses become more challenging with cable length and lessen with higher voltage [17].

2) Power Profile

The comparison is most easily seen graphically. The nodes represent the power between each busbar on Fig. 4, where UGI is power injected into the grid.

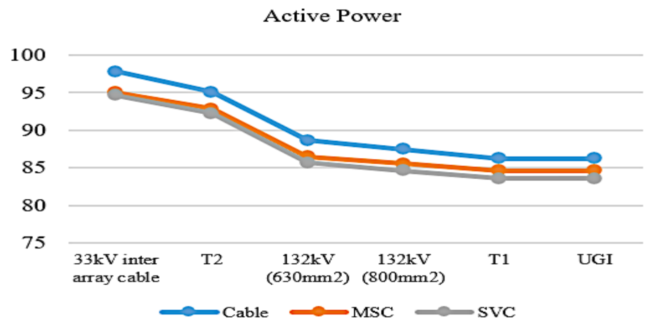

Fig. 9. Active power for Model 1

Figure 9 and Figure 10 indicate the power profile of three different models: cables, MSC and SVC. In Figure 9 there is a clear trend of declining real power from the MV transmission (33 kV inter-array cable) to the HV transmission (UGI) for all design models. Cable has the highest active power followed by MSC and SVC. One of the benefits of MSC added in the transmission line is the improvement of the active power transmission capacity and transient stability margin.

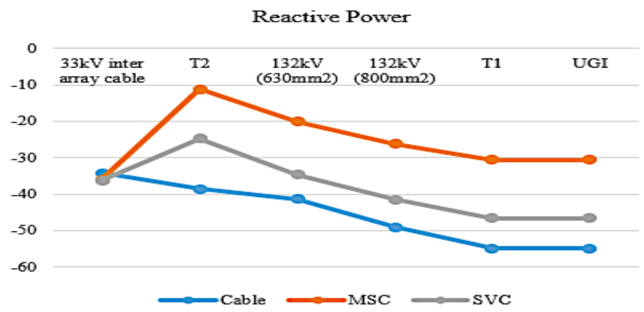

Fig. 10. Reactive power for Model 1

It is apparent from Figure 10 that MSC has the lowest reactive power compared to SVC and cable. The MSC reactive power was swiftly reduced from the 33 kV inter-array transmission lines to T2 (transformer), then the reactive power increased steadily to the grid at UGI. The reactive power at T2 reduces approximately 71% compared to the cable model. MSC compensates for the steady state of reactive power in the system by switching only a few times a day. While for the SVC the reactive power decreased at T2, as it provided active compensation due to the fast switching capability. The device absorbed reactive power in sub cycle time frames. The reactive power then increased at 132 kV until the UGI. The problem with SVC, because of the capacitor devices, is they suffer the same degradation in reactive capability as voltage drop. Moreover, once it exceeds its reactive generation limit, voltage instability may exist as the critical or collapse voltage becomes voltage controlled by the SVC. As for cable, the reactive power slightly reduced at

T2 and rose onwards from the 132 kV (export cable). This result is explained by the fact that the MSC method is better than SVC in the reactive power compensation application.

B. Model 2: Upgrading Inter-Array Cable to 52 kV (HV) and Comparison to 33 kV (MV)

Model 1 was then upgraded to a 52 kV inter-array cable keeping the MSC device as shown in Fig. 11; the conventional design using 33 kV inter-array cable is illustrated in Figure 12. Also between Figure 11 and Figure 12 the number of inter-array cables used is reduced from 2 to 1. Interestingly, the generated active power at 52 kV was higher compared to 33 kV.

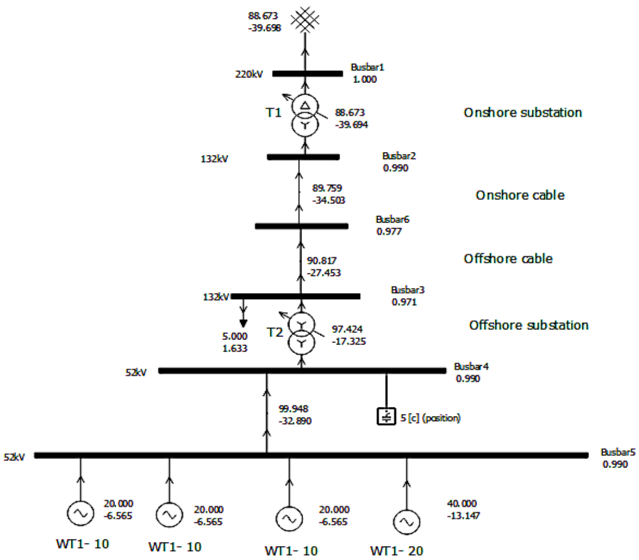

Fig. 11. Model 2: MSC device with 52kV inter-array cable

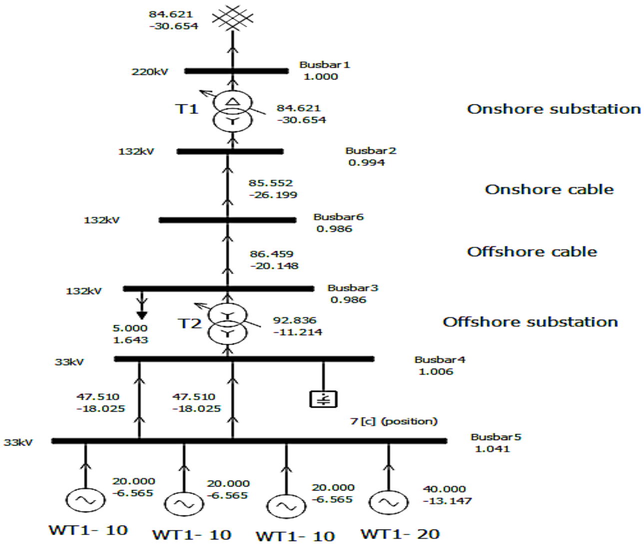

Fig. 12. Model 1.2: MSC device with 33kV inter-array cable

It is apparent that the 52 kV inter-array cable model is capable of generating more active power, 51%, compared to the 33 kV inter-array cable, 49%. It can be concluded that the higher the voltage in the inter-array cable, the higher active power produced in the transmission system.

52 kV produced lower reactive power compared to 33 kV for both RPC methods. Therefore we can conclude that the higher the cable voltage in the transmission network, the lower the reactive power output and the more this power can be absorbed by the RPC devices

In this study, copper cable was selected as the conductor and the resistivity value of this material is taken from Table VI (see Appendix). The resistance of 33 kV and 52 kV inter-array cable were found to be 8.26 Ω and 10.434 Ω respectively. This shows that the resistance of the 52 kV cable increased by about 26% compared to 33 kV cable. The I^2R losses in the transmission system are shown in Table 1. Since the MSC design 33 kV is connected to two cables, the losses ought to be doubled. The result in this table proved that the losses associated with the 52 kV model when compared with the 33 kV model were less. It is an important point, as losses can be capitalized on monetary terms. This monetary value can be significant over the life of a project. According to [18], the active power losses in the 66 kV wind farm are always lower, between 0.3 and 11% less than in the 33 kV wind farm in all cases. Closer inspection of the Table I shows that active losses in 52 kV cable were 1.70% compared to 33 kV cable.

TABLE I. ACTIVE POWER LOSSES

	33kV (MW)	52kV (MW)	Deduction	%
120mm²	263.66	-	-4.48	-1.70
95mm²	-	259.18		
630mm²	0.72	0.72	0	0
800mm²	0.0139	0.0139	0	0

As per [16], the prices for 66 kV wet type cables would be between 10% to 20% higher than for 33 kV cables of the same type and diameter, which is far more than outweighed by a doubling of the transfer capacity. The additional fact that the total cable length would be lower for 66 kV solution provides an added benefit. Moreover, the 66 kV cable insulation material operates at higher electrical stress (> 6 kV/mm) than 33 kV cables, requiring stringent cable design and selection of insulated material. The evidence from these results indicated that the cost of MV cable (33 kV) is more expensive than HV cable (52 kV) because it carries larger current.

C. Model 3: MSC Direct Connected at HV Side (Replace Transformer) and Comparison with SVC at MV Side

RPC supplier, Siemens, confirmed that an MSC can be directly connected to the HV voltage and thus no transformer is required in the layout. Hence, the model in Fig 13 is used to analyze the load flow with an MSC applied to the HV side substituting for the transformer device. This modeling uses PowerWorld, please note the results include voltage angle and current flow as a percentage of rating. The result from this model shows that there was a slight reduction in active power along the transmission system. This loss occurred because the capacitors in the MSC reduce the apparent power during the entire transmission by injecting the reactive power into the system [19]. Simultaneously, the production of reactive power increased dramatically from bus 6 to bus 2. This is due to MSC injecting reactive power, 50 Mvar, from bus 1.

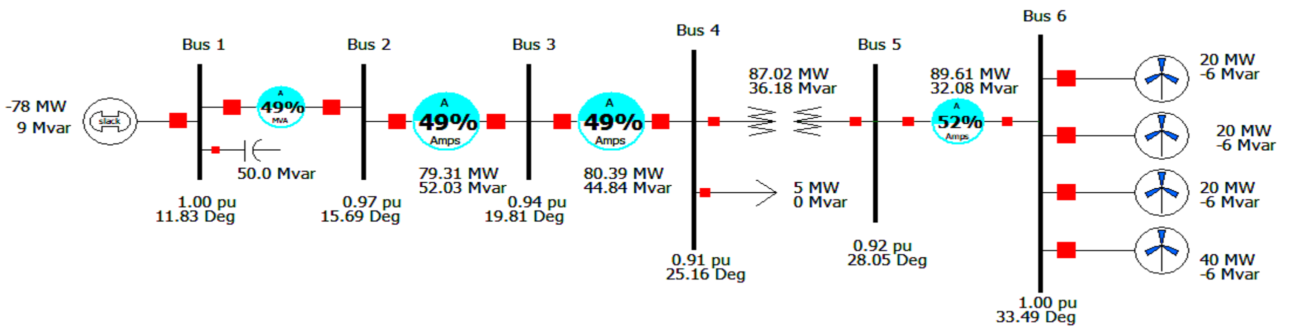

Fig. 13. MSC applied at HV side (replace the transformer)

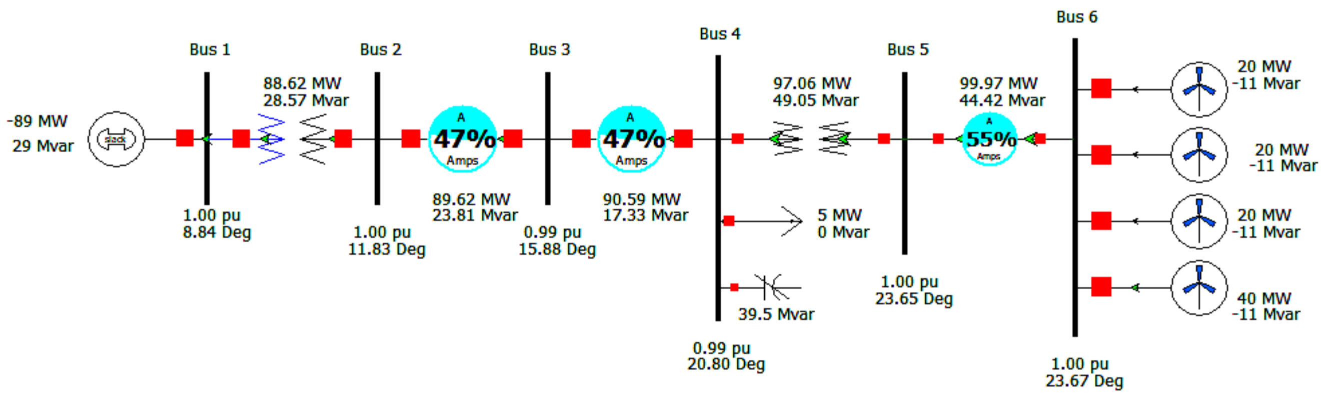

Fig. 14. Transmission network with SVC Design at MV Side

Fig.14 presents the result obtained from the SVC design. What is striking about this result is the reactive power decreased to 17.33 Mvar at export cable (between bus 4 and bus 3) and it increased again until it reached the slack generator. What happened at this point is the SVC controlled the voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When the system voltage is high, it absorbs the reactive power (SVC became inductive) and minimizes the reactive power transported to the system and improves power quality of active power as well as stabilizing the voltage [20]. Meanwhile, the generated active power decreases from bus 6 to the slack generator. Comparing both figures, it signifies that SVC generated more active power than MSC. The losses in active power of MSC design occurred because the capacitors in the MSC reduced the apparent power in the entire transmission by injecting the reactive power into the system.

Although the output of active power was significantly greater for the SVC model; with respect to initial cost and maintenance the MSC layout offers other benefits, partucularly economic value. According to the information provided by Siemens, the installation of an HV transformer would be more expensive than MSC. In addition, the maintenance cost for MSC is negligible (visual inspection and regular cleaning depending on pollution level). As for the SVC, the design of this system was intended to provide reactive and load imbalance compensation [21].

V. Conclusion

A key advantage of transferring to a higher voltage inter-array cable is the ability for higher power transmission over the same or lower cross-sectional area cable. In this study, the 52 kV cable is capable of generating more active power (51%) compared to 33 kV inter-array cable (49%), installed in offshore wind farms. Theoretically, the active power losses for 66 kV are usually lower, between 0.3% to 11% than the 33 kV layouts. The marginal losses in MSC design for the 52 kV cable were 1.7% compared to 33 kV. The important outcome of converting to a higher voltage is that fewer cable strings enter the network, as more wind turbines can be attached per row compared to 33 kV. This results in substantial capital cost savings in terms of both cable procurement and installation. It also reduces losses in the system, reduces the overall cable length and the number of substations.

The simulation in these models was to determine the distribution of reactive power effects in the operation of different components and subsystems of the power system such as transformers and cables. The results in this study showed that there is a small reduction in active power. By comparison, the reactive power increased gradually from the MV side to the HV side. Moreover, the power profile revealed that SVC generates more active power compared to MSC. Although, the SVC model is more efficient at producing active power, MSC models are cheaper than SVC. Siemens confirmed that MSC can be mounted on the HV side and replace the task of the transformer. The benefit of the MSC is that capital costs and maintenance will be cheaper. Finally, by providing various topology models, the energy providers can determine which is the most efficient implementation within the power transmission network

VI. Future Work

For future work there will be a comparison with HVDC transmission. This could improve power quality and further minimize the overall cost. Besides that, investigating results with different types of cross-sectional cable will be useful. This will provide a variable result of losses, mag voltage, and active and reactive power. It will also offer energy providers several options for implementing and addressing transmission systems related to issues with optimum cost.

Acknowledgment

Thanks to the Siemens supplier that supported my research by providing information and prompt responses to my inquiries.

Appendix

TABLE II. Transformers Parameters

No	Capacity (MVA)	Voltage (kV)	Zpu	Rpu	Xpu	Tap (%)
T1	225	220/132	0.059	0.0115	0.055	Max=+10% Min= -10%
T2	112.5	132/33	0.046	0.0243	0.0387	Max=-20% Min=+10%

TABLE III. Cable Parameters

Voltage (kV)	Size (mm^2)	R (Ω)	X(Ω)	Rpu	Xpu	Length (km)
33	120	0.018	0.0116	0.0975	0.0628	59
52	95	$0.1796e^{-3}$	$0.18e^{-3}$	$0.243e^{-3}$	$0.243e^{-3}$	59
132	630	0.0395	0.209	0.017	0.09	75
132	800	0.0324	0.217	0.0112	0.0747	60

TABLE IV. RPC Parameters

Voltage Cables	RPC	Parameter Data
33kV	MSC	No. of Capacitor Steps = 10 Capacitor Step Size (Mvar) = 4
	SVC	Max. voltage (pu) = 1.2 Min. voltage (pu) = 0.8 Min. Mvar = -5 Max. Mvar = 30
52kV	MSC	No. of Capacitor Steps = 5 Capacitor Step Size (Mvar) = 4
	SVC	Max. voltage (pu) = 1.2 Min. voltage (pu) = 0.8 Min. Mvar = -5 Max. Mvar = 30

TABLE V. Wind Turbine Parameters

Each Turbine = 2MW Power Factor = 0.95			
Row Line	Wind Turbine per Row	Total Rating (MW)	Total Rating (Mvar)
1	10	20	-6.565
2	10	20	-6.565
3	10	20	-6.565
4	20	40	-13.147

TABLE IV Resistivity Table

Material	ρ (Ω – m) resistivity at 20° C	Material	ρ (Ω – m) resistivity at 20° C
Silver	1.59×10^{-8}	Nichrome	1.10×10^{-6}
Copper	1.68×10^{-8}	Carbon (Graphite)	2.50×10^{-6}
Gold	2.24×10^{-8}	Germanium	4.60×10^{-1}
Aluminium	2.82×10^{-8}	Drinking water	2.00×10^{-1}
Calcium	3.36×10^{-8}	Silicon	6.40×10^{2}
Tungsten	5.60×10^{-8}	Wet wood	1.00×10^{3}
Zinc	5.90×10^{-8}	Glass	10.0×10^{10}
Nickel	6.99×10^{-8}	Rubber	1.00×10^{13}
Iron	1.00×10^{-7}	Air	1.30×10^{16}
Lead	2.20×10^{-7}		

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