DESIGN APPLICATION OF A FILTER FOR A DOUBLY FED INDUCTION GENERATOR (DFIG) AND DC WINDFARM INTEGRATED WITH AN IMPROVED DC COLLECTION GRID AND HYBRID BASED HVDC LONG DISTANCE TRANSMISSION

by

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EXTENDED ABSTRACT

There had been an increased concern of global and environmental issues that has prevailed for existing conventional energy sources such as oil, natural gas, fossil (coal). There had been great efforts by governments around the world to address these issues through the implementation of renewable programs and policy through exploitation of wind energy. The wind power industry is developing rapidly and has undergone significant transformation with massive penetration of wind turbines because it is friendly to the environment.

Many wind turbine farms employ the DFIG because of the significant advantages that it offers such as improved power quality, high efficiency, the power converter only deals with fractional power (rotor power) and improved controllability of the reactive and active power through de-coupling control.

With the increase in wind power plant installations offshore and the need to satisfy technical grid code compliance, HVDC has become the preferred option to HVAC for connecting or integrating offshore power plants to the power systems grid.

Integration and increased penetration of wind farms to the grid pose great challenges because of the fluctuating wind speed and long-distance transmission of wind power. Currently there are two technologies and application, namely the CSC and VSC. The CSC tend to be a well-established technology than VSC and has much attributes like higher power capability, lower losses and lower losses. There are limitations when CSC technology is used to include larger footprint due to filter requirement and the requirement of external reactive power compensation to support the commutation of the converters. To address some of these challenges, VSC(HVDC) has proven to be the best technology needed in modern wind power conversion system to make it feasible for the DFIG to achieve variable speed operation,

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independent control of active and reactive power and to make it easy to utilize the benefits of Maximum Power Point Tracking (MPPT) and the last but not the last least provide de-coupled active and reactive power control which enhances the stability of both offshore wind farm and onshore grid.

To harvest the advantages of CSC and VSC HVDC, a hybrid technology application of VSC and LCC HVDC is proposed for long distance bulk transmission to leverage the advantages of both technologies and minimizing the disadvantages of both technology.

The operation of some configuration of VSC and all LCC(CSC)-HVDC converters creates harmonics because of the inherent non-linear characteristics of the internal power electronics. The presence of harmonics in the wind farm can be a nuisance because of the voltage and current distortion that it causes. The problem can be compounded if there are series and parallel resonant points in the wind farm plant. Hence the need to identify harmonic currents measuring points and implement mitigation methods.

It is well known that the conventional offshore windfarm has been implemented and a mature technology and constructed using an AC collection grid to integrate to the wind farm. This requires an offshore platform substation that will convert the AC to DC through a converter and a step-up transformer thus adding more weight, increasing the size of components to the offshore platform and introducing an increased in cost due to the additional components required. Hence, the need to introduce a more efficient and effective way of collecting DC power leading to a current significant interest in research on efficient DC collection system.

Recently, the DC collection system for interconnecting wind energy conversion system has been an area that has gained significant research interest where the output of the wind turbine can be DC integrated to a DC converter booster located inside the wind turbine enclosure integrated to an internal DC bus which is stringed together to be integrated with a grid side offshore main transmission DC to DC converter with medium frequency and high-power application to step up the voltage through various stages to include low voltage to medium

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voltage and from medium voltage to high voltage. There are several topological layouts that can be explored to select the most efficient topology based on the analysis of cost and transmission system losses.

Though the DC grid collection system has gained research interest and there had been a few literatures and research done in the past on different layouts and configuration to determine the best cost effective outline and lower transmission losses, at that time the research was conducted most of the components of the DC grid collection system has not been realized and commercialized and were still in research stage, as such most of the parameters used for the analysis are not realistic in the present day that the components have been realized and commercialized. This provides a good opportunity to revisit these dissertation, identify the gaps and perform an improved modelling of the DC windfarm and analysis of the DC collection system.

In the past research performed on the DC collection system and DC wind farm, the transmission distances used for the cable are not realistic thus providing a window of opportunity to revisit this model to perform an improved model simulation with appropriate transmission cable distances.

Also, the few literatures on DC wind farm and DC collection system did not provide a model of DC windfarm that will integrate to a Hybrid Main HVDC converters to leverage the advantages of both converter technology and analyse the interactions of the windfarm with the converter and the power systems.

Though the DC collection grid integrated to a DC windfarm had been proposed by many researchers to be very economical, there are other challenges that need to be addressed to include DC faults which tend to be problematic and performing simulation analysis to

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determine the response of the wind turbine, power converters, the grid system, and the high frequency model of cables to DC faults.

In the past research conducted, the researchers failed to perform harmonic system analysis to check the presence of any harmonics and resonance points and implementation of applicable filters. Also, a simulation was not performed to see then interactions between then filters, converters, wind turbine and power systems during unbalanced conditions.

In the past research, the pi model used for the cable modelling does not account for high frequency components and applicable for steady state applications. To achieve an improved model of the windfarm, a high frequency model of the cable should be used which will be able to improve upon the accuracy of high frequency model for internal faults and transients associated with it.

In the past research and contributions performed, the interaction of wind turbine and the DC to DC converter for an external grid fault was not considered, this provides a good platform to perform an improved DC windfarm simulation to show the interaction of the wind turbine and the converters during external faults.

The past research suggests exploring the use of an MMC topology or configuration for the DC to DC converter to improve upon the power quality and efficiency and a better modulation strategy to be adopted for the MMC configuration.

The past research also suggests a further research need to be performed on DC collection point and wind turbine fault and implementation of a robust protection scheme during DC faults.

The outline that proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes or groups of aggregate model of total wind turbine generation source totalling 1800MW at 50Hz. The first node generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together

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to form the main offshore AC collector bus with an output of 33kVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from 33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore. The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV dc grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV DC grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load and synchronous generation source rated at 1000MW at 60 Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to a step-up power transformer and main power system grid with a rating of 2800MW, 400KV, 50Hz

This research will take a different approach into the design of the most efficient DC windfarm topology compared with the traditional AC farm based on the analysis of transmission system losses, cost and utilization of realistic transmission cable distances, realization and

commercialization of most components of the DC grid collection system. The research will take a different approach of proposing and implementing an improved model of the DC windfarm that will utilize high frequency model of the cable in the model. The improved model will evaluate the response of the wind turbine and the interaction of the converters and the power system for internal and external faults (A.C and DC). The improved model will also evaluate the presence of harmonics and resonance in the topology outline and the possible design of robust filters to mitigate these harmonics and test the response of the filters to unbalanced conditions. The improved model will implement a robust protection system for DC faults and the implementation of an efficient and better converter topology for the main DC to DC converter and generation side converters.

This research will take a different approach of integrating the DC wind farm and DC grid collection system with a Main Transmission Hybrid HVDC converter.

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INTRODUCTION

There had been increasing demand of energy to support the needs of modern society and the current energy sources such as the coal and oil-fired plants produces an enormous air pollution that has caused global warming concern. Based on the current concerns for global warming, pollution, planet safety, oil reserves and environmental awareness there had been a significant growth of the renewable energy sources to support the needed generation demand and wind generation has been one of the fastest growing energy generation sector worldwide and a perpetual source of power that with an efficient capability. In addition, the advancement in power electronics has supported the growth of the wind turbines.

Wind farms can be connected to the onshore grid through HVAC and HVDC connections. But HVDC connections have proven to be the most economical and technically most beneficial connection for wind farms that are located more than 75km from the onshore A.C grid.

There are significant challenges that are faced when integrating wind farms to the power system grid and to overcome this challenges HVDC has become an accepted technology of choice to integrate the wind farm to the power system grid and to facilitate the transfer and interchange of power from the offshore wind power plant to the onshore grid.

Network operators have implemented grid codes and connection agreement to provide a seamless connection to the grid from wind power plants without any adverse effects on the existing grid and the HVDC technology has provided the needed support to meet some of these requirements.

Below is a summary of some of the challenges faced during the integration of the DFIG to the grid

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- The source of wind is not regular, very difficult to predict and it is intermittent which can make it very difficult to harness energy out of a wind farm based on a schedule. Though there are availability of weather forecast technologies, they are not accurate at times. The fluctuating power can lead to problems like voltage flicker and balancing the demand.
- Early generation of wind turbine do not have the capability to provide reactive power compared to synchronous generators thus a limitation on voltage stability

There are four different types of wind turbine namely Fixed Speed type 1 or A, Partial Variable Speed with variable rotor type B or type 2, Doubly Fed Induction Generator with partial rated converter type C or 3 and lastly the Doubly Fed Induction Generator with full converter rating. Out of these wind turbines identified above the Doubly Fed Induction Generator type 3 has proven to be the wind turbine of choice to be used to integrate HVDC because of the significant advantages to include high efficiency, excellent quality of power, utilization of partial scale converter reducing switching losses, installation footprint, improved reactive and active power control and cost. The DFIG uses a variable speed controlled wind turbine and has the advantage that the VSC converter does not need to be rated to the machine full rated power. The rotor side converter provides the active and reactive power control of the machine and the grid side converter keeps the D.C link voltage constant. The stator phase windings of the DFIG are connected directly to the grid while the rotor is connected to a back to back voltage converter through slip rings. The rotor speed and frequency is controlled by the voltage sourced converter with a speed range of +/-30% of the synchronous speed.

The advantages of the DFIG are

- It has the capability of decoupling the control of the active and reactive power by controlling the rotor terminal voltages
- The construction is much simpler and cheaper compared to other types of wind turbines

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- The power converter rating is typically +/-30% of the full rating of the rated power and this leads to a lot of advantages such as cost reduction for the converter, less switching losses, less harmonic injection to the grid and a much reduction in the size of the filter. In a nut shell, improved efficiency is obtained.

The disadvantages of the DFIG are

- The requirement of a slip-ring and gearbox will require a lot of maintenance and consequential cost from increased maintenance
- To be able to achieve a fault ride through capability, several protection schemes have implemented.

The advantages shown below makes the DFIG an excellent choice to integrate to a VSC

- It permits or allows continuous and independent control of real and reactive power
- The reactive power control is independent at each terminal
- It has a simpler configuration interface with the A.C system
- The converter can be used to synthesize three phase voltages similar to a synchronous machine
- Can be used best in extremely weak system
- It does not require polarity reversal when power reversal is needed
- It has an excellent black-start capability
- No possibility of commutation failures
- It has a minimal amount of impact on the environment
- The level of power quality is very high

It is well known that the conventional offshore windfarm has been implemented and a mature technology and constructed using an AC collection grid to integrate to the wind farm. This

requires an offshore platform substation that will convert the AC to DC through a converter and a step-up transformer thus adding more weight, increasing the size of components to the offshore platform and introducing an increased in cost due to the additional components required. Hence, the need to introduce a more efficient and effective way of collecting DC power leading to a current significant interest in research on efficient DC collection system.

Recently, the DC collection system for interconnecting wind energy conversion system has been an area that has gained significant research interest where the output of the wind turbine can either be AC or DC which can be integrated with a DC to DC converter to step up the voltage through various stages to include low voltage to medium voltage and from medium voltage to high voltage.

The application of DC to DC converter which utilizes a medium frequency transformer has been realized. This DC to DC converter is used to boost the output voltage of the wind farm or step-up the intermediate DC collection grid voltage and has provided lot of merits or advantages to include the elimination of large bulky power transformer, reduced weight on the offshore substation platform, reduction in size and increase in efficiency.

Though the DC grid collection system has gained research interest and there had been a few literatures and research done in the past on different layouts and configuration to determine the best cost effective outline and lower transmission losses, at that time the research was conducted most of the components of the DC grid collection system has not been realized and commercialized and were still in research stage, as such most of the parameters used for the analysis are not realistic in the present day that the components have been realized and commercialized. This provides a good opportunity to revisit these dissertation, identify the gaps and perform an improved modelling of the DC windfarm and analysis of the DC collection system.

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In the past research performed on the DC collection system, the transmission distances used for the cable are not realistic thus providing a window of opportunity to revisit this model to performed an improved model simulation with appropriate transmission cable distances.

In the past research conducted, there was no robust harmonic and resonance system analysis performed and the application of the right filters performed and a simulation performed to see the interactions between the filters, converters, wind turbine and power systems during unbalanced conditions (A.C and DC Faults).

In the past research, the pi model used for the cable modelling does not account for high frequency components. To achieve an improved model of the windfarm, a high frequency model of the cable should be used which will be able to improve upon the accuracy of high frequency model for internal faults and transients associated with it.

In the past research and contributions performed, the interaction of wind turbine and the DC to DC converter for an external grid fault was not considered, this provides a good platform to perform an improved DC windfarm simulation to show the interaction of the wind turbine and the converters.

Though there have been a few research literatures on the DC windfarm and DC collection system, none of them proposed a model that will integrate it to Hybrid Main Transmission HVDC, this provides a platform for a model to be done on that.

The past research suggests exploring the use of an MMC topology or configuration for the DC to DC converter to improve upon the power quality and efficiency and a better modulation strategy to be adopted for the MMC configuration.

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The past research also suggests a further research need to be performed on DC collection point and wind turbine fault and implementation of a robust protection scheme during DC faults.

The past research also suggests a further research and analysis to be performed on the interaction of the wind turbine and the converters with the power system under DC faults.

During the operation of DFIG and PMSG wind turbines based on voltage sourced technology, harmonics are produced by the power converters and injected into the grid because of the non-linearity of the semi-conductors used in the converters. Non-linear devices such as the power electronics used in these converters inject harmonic currents into the power system grid from their operation

The flow of harmonics leads to detrimental effects on the power quality of the grid and have a consequential effect on the operation of protective relays, switchgears, rotating machinery and installed measuring device.

The emergence of the power electronic devices in power systems has caused international agencies like IEEE and IEC to develop standards regarding harmonics. There is an IEEE standard 519-2014 that stipulates the recommended limits on harmonic current that are injected by these non-linear loads and the voltage distortion limits that that a consumer is expected to receive from the supply system. The guidance provided on the limits for harmonics are used for the design of filters.

The outline that proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes of aggregate model of total wind turbine generation source totalling 1800MW, 50Hz. The first node or group of generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 33KVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from

33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore. The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV DC grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV dc grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load and synchronous generation source rated at 1000MW, 60Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to a step-up power transformer and main power system grid with a rating of 2800MW, 50Hz and 400KV

The wind power when generated need to be integrated to the grid through the most less costly technology. The grid side Main Hybrid HVDC used as long bulk HVDC transmission has proven to be the technology of choice because it leverages achieving high power and voltage rating, lowering the high capital cost and high frequency switching losses inherent in voltage sourced converter. The modular scale of this configuration which leads to a reduction in

footprint and the integrated DC to DC converter to step up the DC voltage on the wind generation side eliminates the high cost associated with then step up transformer.

This research will take a different approach into the design of the most efficient DC windfarm topology compared with the traditional AC farm based on the analysis of transmission system losses, cost and utilization of realistic transmission cable distances, realization and commercialization of most components of the DC grid collection system. The research will take a different approach of proposing and implementing an improved model of the DC windfarm that will utilize high frequency model of the cable in the model. The improved model will evaluate the response of the wind turbine and the interaction of the converters and the power system for internal and external faults. Then improved model will also evaluate the presence of harmonics and resonance in the topology outline and the possible design of robust filters to mitigate these harmonics and test the response of the filters to unbalanced conditions. The improved model will implement a robust protection system for DC faults and the implementation of an efficient and better converter topology for the main DC to DC converter and generation side converters

This research will involve the proposal of a modified control strategy for the rotor side converter, grid side converter, modified control strategy for the DC to DC converter, modified control strategy for the hybrid HVDC converter, control strategy for the proposed filters, validation of the proposed control strategy and design of an applicable filter utilizing steady state modelling analysis in PSCAD. In addition, the model will be Compliant to Fault Ride Through (FRT) capabilities and the control scheme will be modified to withstand the dynamic response of the model during balance and unbalance faults at the grid side HVDC hybrid converter and the DFIG point of coupling.

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SIGNIFICANCE AND BENEFITS OF DISSERTATION TOPIC

- The DC to DC converter with a medium and high frequency transformer which has been used in various stages of the outline topology and used to boost the output voltage of the wind farm or step-up the intermediate DC collection grid voltage will provide lot of merits or advantages to include the elimination of large bulky 50/60Hz power transformer, reduced weight on the offshore substation platform, reduction in size, reduction in cost, reduction in maintenance cost, realization of a robust and highly reliable DC switchgear and collection system and increase in efficiency. Also, great significant cost savings when compared with the traditional AC collection system.
- In an ideal world, it is expected that an HVDC converter should be able to operate at full power and desired power factor, import and export power, eliminating failure, have low switching loss and cause no significant harmonic flow. The Hybrid HVDC which employs the traditional LCC HVDC and the newer technology which is called the VSC will mitigate or eliminate some of the weakness of the LCC technology with the utilization of the VSC technology to eliminate the need for external reactive compensation. It also improves some of the weaknesses of the VSC to include minimizing the high switching losses based on the level of converter being used. The LCC HVDC technology allows higher rating of power to be used. The integration hybrid allows the terminal voltage to be controlled and also the real power and possibly reactive power exchange.
- It also eliminates the traditional large bulky filters associated with the LCCHVDC converters and the elimination of harmonics and resonance points if identified and mitigated will eliminate the undesired effects of harmonics on power system equipment components.

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- The enhanced or improved DC wind Farm and DC collection grid will provide a platform for more reliable and efficient transmission system to be achieved with less transmission losses, and less cost.

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RESEARCH TASKS COMPLETED SO FAR

- Tested Successfully the first aggregate or node of generation(DFIG)-600MW of topology layout in PSCAD/EMTDC software application, the output waveform for the voltage and power had a few oscillations which was due to the right control parameters which will require further tuning of the control parameters

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STATEMENT OF THE PROBLEM

Quite recent the DC collection system for interconnecting DC wind energy conversion system has been an area that has gained significant research interest where the output of the wind turbine can either be AC or DC which can be integrated with a DC to DC converter to step up the voltage through various stages to include low voltage to medium voltage and from medium voltage to high voltage.

This DC to DC converter which uses a medium or high frequency transformer is used to boost the output voltage of the wind farm or step-up the intermediate DC collection grid voltage to a higher voltage. The merits associated with the application of the DC to DC converter include the elimination of large bulky power transformer, reduced weight on the offshore substation platform, reduction in size and increase in efficiency.

Though the DC grid collection system has gained research interest and has been deemed to be very economical, there are still some challenges with the DC grid implementation that will require more research.

When these researches were conducted most of the components of the DC grid collection system has not been realized and commercialized and were still in research stage, as such most of the parameters used for the analysis are not realistic in the present day that the components have been realized and commercialized by ABB, Siemens and Alstom. This provides a good opportunity to revisit these dissertation, identify the gaps and perform an improved modelling and analysis of the DC windfarm and DC collection system

The few past researches performed on the DC collection system and DC wind farm, the transmission distances used for the cable are not realistic thus providing a window of opportunity to revisit this model to performed an improved model simulation with appropriate transmission cable distances.

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Though there have been a few research literatures on the DC windfarm and DC collection system, none of them proposed a model that will integrate it to Hybrid Main Transmission HVDC, this provides a platform for a model to be done on that.

The past research conducted, the authors failed to address and perform a robust harmonic and resonance system analysis and implement any filters that might be needed. In addition, the authors failed to perform simulation to see the interactions between the filters, converters, wind turbines and power systems grid during unbalanced conditions.

In the past research, the authors used a pi model for the cable modelling, but the drawback with this model is that it does not account for high frequency components. To achieve an improved model of the windfarm, a high frequency model of the cable should be used which will be able to improve upon the accuracy of high frequency model for internal faults and transients associated with it.

In the past research and contributions performed, the interaction of wind turbine and the DC to DC converter for an external grid fault was not considered, this provides a good platform to perform an improved DC windfarm simulation to show the interaction of the wind turbine and the converters.

The past research suggests exploring the use of an MMC topology or configuration for the DC to DC converter to improve upon the power quality and efficiency and a better modulation strategy to be adopted for the MMC configuration.

The past research also suggests a further research need to be performed on DC collection point and wind turbine fault and implementation of a robust protection scheme during DC faults.

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The past research also suggests a further research and analysis to be performed on the interaction of the wind turbine and the converters with the power system under DC faults.

The outline that proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes or groups of aggregate model of total wind turbine generation source totalling 1800MW, 50Hz. The first node generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 33kVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from 33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore. The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV dc grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV dc grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load and synchronous generation source rated at 1000MW, 60Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to

a step-up power transformer and main power system grid with a rating of 2800MW, 400KV, 50Hz.

This research will take a different approach into the design of the most efficient DC windfarm topology compared with the traditional AC farm based on the analysis of transmission system losses, cost and utilization of realistic transmission cable distances, realization and commercialization of most components of the DC grid collection system. The research will take a different approach of proposing and implementing an improved model of the DC windfarm that will utilize high frequency model of the cable in the model. The improved model will evaluate the response of the wind turbine and the interaction of the converters and the power system for internal and external faults. Then improved model will also evaluate the presence of harmonics and resonance in the topology outline and the possible design of robust filters to mitigate these harmonics and test the response of the filters to unbalanced conditions. The improved model will implement a robust protection system for DC faults and the implementation of an efficient and better converter topology for the main DC to DC converter and generation side converters.

This research will propose an improved model that will integrate to a Hybrid HVDC main transmission converter.

This research will also involve the proposal of a modified control strategy for the rotor side converter, grid side converter, modified control strategy for the dc to dc converter, modified control strategy for the hybrid HVDC converter, control strategy for the proposed filters, validation of the proposed control strategy and design of an applicable filter utilizing steady state modelling analysis in PSCAD. In addition, the model will be Compliant to Fault Ride Through (FRT) capabilities and the control scheme will be modified to withstand the dynamic

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response of the model during balance and unbalance faults at the grid side HVDC hybrid converter and the DFIG point of coupling.

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RESEARCH AIM OR OBJECTIVE

The objective of this research is to take a different approach into the design of the most efficient DC windfarm topology compared with the traditional AC farm based on the analysis of transmission system losses, cost and utilization of realistic transmission cable distances, realization and commercialization of most components of the DC grid collection system.

The research will take a different approach of proposing and implementing an improved model of the DC windfarm that will utilize high frequency model of the cable in the model and evaluate the response of the wind turbine and the interaction of the converters and the power system for internal and external faults.

An improved model will be implemented to offer a robust protection system for DC faults.

The improved model will also evaluate the presence of harmonics and resonance in the topology outline and the possible design of robust filters to mitigate these harmonics that will be present in the operation of the topology in figure 1 and test the response of the filters to unbalanced conditions

The outline that proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes or groups of aggregate model of total wind turbine generation source totalling 1800MW, 50Hz. The first node or group generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 33kVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from 33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore.

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The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV dc grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV dc grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load and synchronous generation source rated at 1000MW, 60Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to a step-up power transformer and main power system grid with a rating of 2000MW, 400KV, 50Hz.

This research will also involve the proposal of a modified control strategy for the rotor side converter, grid side converter, modified control strategy for the DC to DC converter, modified control strategy for the hybrid HVDC converter, control strategy for the proposed filters, validation of the proposed control strategy and design of an applicable filter utilizing steady state modelling analysis in PSCAD. In addition, the model will be Compliant to Fault Ride Through (FRT) capabilities and the control scheme will be modified to withstand the dynamic response of the model during balance and unbalance faults at the grid side HVDC hybrid converter and the DFIG Point of Common Coupling.

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MAIN LITERATURE CONTRIBUTORS TO RESEARCH TOPIC

The main literature contributions for this research are

[Haiboz Zhang, Diana Florez, Christophe Saudemont, Francois Gruson, *Control Strategies of a DC Based offshore WindFarm with Series connected Collection Grid" IEEE, ISSN:978-1-5090-0058-6, 2016*]. In this paper, the authors proposed and presented a control strategy for a series connected DC windfarm which is integrated to an onshore MMC. The authors asserted that the advantage of this series connection is it makes it easy to achieve the required transmission level voltage level, eliminating an offshore step-up transformer and booster DC to DC converter. The authors further stated that though economically feasible there are still some challenges associated with this to include there are large output voltage fluctuations when there is variation of wind speed, unbalanced condition or when a wind turbine has been removed or isolated from service. The authors presented an overvoltage limitation control strategy to make each wind is operating safely within its voltage limits. However, though the simulation was successful in PSCAD, there were some resonance points which the authors proposed for future research. The following gaps were identified with this literature contribution or the literature provides an area for research

- A combination of a series and parallel arrangement can be proposed as an alternative generation set unit.
- The literature did not use any high frequency model of the cables that was used for simulation. This makes it impossible to simulate the effects and interactions of the high frequency model of the cable with the wind turbine, MMC converters and the grid. This provides a window opportunity to perform a research in that area
- The literature did not make mention of any robust filter design to eliminate any harmonics and resonance points that might be present. This provides a window of research opportunity for analysis of harmonics and resonance and installation of mitigation filters.

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- The paper or literature did not address any starting sequence of the components and the wind turbines
- The paper also failed to address any unbalanced fault conditions like DC and AC faults and appropriate isolation strategies and the response of the wind farm and the converters to these unbalanced conditions. This provides another approach to be taken to address this gap.

[He Liu, Mohammed Dahidah, Mathew Armstuge, Najeeji *"Power Electronics Machines and Drives,19th-21st April, 2016*]. In this paper, the authors presented a new high power DC/DC converter that is ideal for offshore wind applications. This proposed converter is used as an internal DC collection point and as a booster converter to be able to integrate the wind generation set to the HVDC main transmission grid. This design approach allows a medium frequency design converter to be used to achieve lower voltage and current stress.

The paper asserted that there are 4 different configurations for the DC to DC converter namely, and out of the configurations below the Input Parallel-Output Series is the best choice of converter. This choice allows soft switching.

- Input Parallel-Output Series(IPOS)
- Input Series-Output Parallel(ISOP)
- Input Series-Output Series(ISOS)
- Input Parallel-Output Parallel(IPOP)

The authors further stated that the recent development of MMC topology makes it a good choice to be used in DC to DC converters to achieve low voltage and low current stress and high output quality with less harmonics. The authors asserted that a choice of DC/DC converter with unidirectional power flow will lower the cost and losses.

The effectiveness of the proposed control strategy was simulated in PSCAD and the results clearly demonstrates a good choice of DC to DC converter.

In reviewing this main literature contribution, the authors have been able to identify a good choice of DC to DC converter which will drive lower voltage and lower current stress and the choice application of a unidirectional converter to eliminate the additional cost and losses but what the authors and the paper fail to address is the following

- Utilize a high frequency model of the selected cable to be able to analyse the high frequency response of these cables and the interactions of the components of the transmission system selected
- The author did not address any unbalanced conditions for AC and DC faults and the response of the components of these topologies to these faults
- The authors did not address any harmonics and resonance analysis to determine if there are any harmonics and resonance points present and how to mitigate these

This opens a research platform to address this gaps that are very necessary to achieve a much reliable transmission system

[Huibin Zhang, Dragan Jovcic *"Interconnecting Subsea DC collection System into a High Reliability Grid, 2014, 5th IEEE PES Innovation Smart Grid, ISSN:978-1-4799-7720-8/14, 2015*]. In this paper, the authors indicated that the DC meshed grid with many converters are seen as economically feasible which makes them a strong choice application in integrating offshore wind energy. The authors asserted that for an AC collection system it is easy for the current to achieve a zero crossing for the fault current to be interrupted but for DC system because of the low impedance the fault arc rises very fast and not able to achieve a zero crossing. The authors indicated that the cost of a DC breaker is about 30% of the cost of the converter. Hence, the authors suggest that to reduce the costly instead of a DC breaker, a DC disconnect switch can be employed. The authors also said that the cost of the DC to DC converter is about 180-200% the cost of the VSC converter proposed and presented a subsea

DC collection grid with a robust control and protection scheme. The authors asserted that though when a DC/DC converter if employed can effectively provide isolation for different sections of topology to isolate the fault effectively a coordinated control scheme is still needed.

In review this paper indicated that to lower the cost of the DC grid collection system, instead of a breaker, a dc disconnect switch can be utilized and to reduce the cost of the DC to DC converter a robust coordinated control scheme can be employed to selectively isolate faults.

However, the authors failed to research in the following areas

- Utilize a high frequency model of the selected cable to be able to analyse the high frequency response of these cables and the interactions of the components of the transmission system selected
- The author did not address any unbalanced conditions for AC and DC faults and the response of the components of these topologies to these faults
- The authors did not address any harmonics and resonance analysis to determine if there are any harmonics and resonance points present and how to mitigate these

[Fujin Ding, Zhe Chen, *"Design of Protective Inductors for HVDC transmission line with DC Grid off-shore Windfarm, IEEE transactions on Power Delivery, Vol 28, #1, Jan 2013*]. In this paper,the authors asserted that the DC grid offers many advantages to include interconnecting wind turbines offshore and the utilization of DC/DC converters with medium frequency transformers offers many advantages to include the elimination of the cost, size and weight associated with the traditional 50Hz/60Hz transformer. The paper further asserted that in the DC grid, a DC fault may result in excessively over voltage and over current in the DC grid which makes protection of the DC grid very much more challenging which will require dedicated and reliable protection systems. The authors stated that there are faster type of DC breakers that are available to include the hybrid DC breakers, IGBT DC breaker but they are

costly to implement. Hence the need to implement a cost-effective solution and that is the introduction of inductors in the transmission system to limit the fault current to prevent damage to the converters. The effectiveness of this proposal was implemented in simulation software.

This paper has presented a cost-effective solution to limit the fault current using inductors during DC fault compared to the use of expensive DC breakers. However, there are gaps that has been identified in this research and that includes

- No High Frequency dependant model of the cable was used and no simulation was performed to evaluate the interference or response of the high frequency model of the cable, the converters, the wind turbine and the power system grid for DC faults in all section of the topology. This provides a window for a research to be conducted in that area.
- No harmonic and resonance analysis was performed to check for the presence of harmonics and mitigation plan. This provides a research window to be performed for harmonic and resonance analysis to be performed and mitigation action to be implemented.
- No AC unbalanced fault analysis was performed to evaluate the response of the converters, wind turbine and the power system to AC fault. This provides a window of opportunity for research to be conducted in this area.

[Sverre Skalleberg, Tore Marvin, *"Control of Direct Driven offshore WindTurbine in a DC collection grid" ISSN:978-14244-8417-1/11, 2011*]. The authors stated that the most dominant drive technology that has been employed for offshore windfarm has been DFIG. In addition to that to achieve a wider speed range of operation and to eliminate the cost of a gear system, attention has been towards the use of PMSG which uses a full-scale converter. The authors stated that there are several topologies for the full-scale converter to include a diode rectifier and DC chopper to step up the voltage and a VSI to interface the grid. This topology though less expensive tend to introduce high harmonic flow. Other topology employs a full-scale

AC/DC VSC on the generator side and a VSI on the grid side but tends out to be more expensive though it has lower harmonics and offers a better control.

To reduce the switching losses and cost, the authors proposed that it is better to get the output voltage of the wind turbine at a level that it will eliminate a converter that will step up the voltage before the central DC to DC converter. The authors in this paper has been able to present the most economical topology on the front end of the generation but within a DC collection grid that is integrated to an AC output and DC output wind turbine there are a lot more challenges that need to be researched into and the authors failed to address this in their paper.

The gaps identified in this paper are shown below

- No High Frequency dependant model of the cable was proposed and used and no simulation was performed to evaluate the interference or response of the high frequency model of the cable, the converters, the wind turbine and the power system grid for DC faults in all section of the topology. This provides a window for a research to be conducted in that area.
- No harmonic and resonance analysis was performed to check for the presence of harmonics and mitigation plan. This provides a research window to be performed for harmonic and resonance analysis to be performed and mitigation action to be implemented.
- No AC unbalanced fault analysis was performed to evaluate the response of the converters, wind turbine and the power system to AC fault. This provides a window of opportunity for research to be conducted in this area.

[Olof Martander, *"DC grids for Wind Farm" Phd dissertation, Chalmers University, Goteborg, Sweden, 2002*]. This dissertation presents and focuses on the DC/DC converters for high

voltage and high-power applications. The author asserted that there are many numerous publications, research on DC to DC converters for low voltage and low power applications and there is now a shift in paradigm to apply the DC to DC converters to medium and high voltage and high-power applications to utilize the merits of the DC to DC converters when compared with the traditional 50/60Hz power transformer. Based on the merits, the dissertation explored the options of using different DC to DC converter topologies for wind farm applications. The author presented a different approach by utilizing 25 wind turbines in 4 different configurations, the first configuration being the traditional AC windfarm outline where the 33KV output of the wind turbine is integrated to a step-up transformer to step up the voltage to 150KV all located offshore, the second configurations being an AC generation source integrated with an HVDC system where the output voltage of the wind turbine is 33KV and step up to 150KV through a HVDC converter, the third and fourth configuration called DC1 and DC2 wind farm layout integrated to a variable speed wind turbine. The wind turbine of the DC1 wind farm layout has an output of 15KVdc to form a 15KV sub-grid and integrated to a 15KV/150KV DC to DC converter. However, a moderate and conserved transmission distance of 20km distance to offshore was used. Present day application will show that these distances can be longer than 20km. The cable lengths from the wind turbine to the DC sub-grid and from the DC sub-grid to the main DC to DC converter might not be realistic. For the DC2 wind farm layout, the output of the wind turbine is 6KVdc to form a 6KVdc sub-grid. The 6KV dc sub-grid is then integrated with two stages of DC to DC converter. The first DC to DC steps the voltage from 6KVdc/30kvdc and the second DC to DC converter steps the voltage up from 30KVdc/150KVdc. Again, the length of cables presented in this dissertation are not realistic and can be higher than this. The author also presented a cost and loss comparison estimates of the 4 configurations and concluded at that time the dissertation was written that cost for DC collection system and DC to DC converter is higher than the traditional AC windfarm, however, at that time the dissertation was written, the DC to DC converter was still in research stage and has not been realized and commercialized and there were other factors that need to be

evaluated such as integration to a higher voltage and also achieve a higher stage ratio to achieve a better cost efficiency. Currently, DC to DC converters have been realized and commercialized, thus a gap has been identified with this dissertation to revisit this dissertation with realistic DC collection cable distances and transmission distances to realize the lower cost and lower losses as envisaged for this choice. Also, the author stated that the higher cost and losses was attributed to the high cost of semi-conductors at that time, but currently the cost of semi-conductors have significantly lowered and switching losses if simulated will be lower now with advancement in technology. Another major gap identified with this dissertation is the failure of the author to identify any robust filter requirement for the wind farm layout, resonance points, utilization of the appropriate high frequency model for the passive elements like cables and the simulation of the response of the converters based on unbalanced faults.

[Lena Max, *"Design and control of DC collection grid for Wind Farm" Phd dissertation, Chalmers University, Goteborg, Sweden, 2009*]. This dissertation presents and focuses on the best design and topology arrangement of an internal DC collection grid system for a wind farm based on cost, design and dynamic operations. The author of the dissertation asserted that for wind farm for offshore applications, space, weight of the components is an important factor to consider and utilization of a DC to DC converter to replace the traditional 50/60Hz power transformer allows less weight and space to be achieved which is a significant advantage for offshore applications and utilization of DC cable for the internal DC grid instead of the traditional AC cable allows lower losses to be achieved. The author also indicated that the utilization of a high-power DC to DC cable makes it possible to achieve a lower output DC voltage rating for the wind turbine and to utilize an internal DC grid.

The author presented three topology options to realize the DC collection grid. The first option is to have a DC to DC converter in each and a second DC to DC converter between the internal

DC bus and HVDC link. The second option is to remove the DC to DC converter in the wind turbine to lower the losses but the drawback is the output voltage is limited by the turbine output. The third option is to remove the DC to DC converter between the internal dc grid and the HVDC link and keep the DC to DC converter in the wind turbine and the high voltage of the HVDC will require a different wind turbine design. Simulation results indicate that the configuration with two DC to DC converters has the highest losses and the topology with one DC to DC converter has the lowest losses. Another approach stated by the author is to connect the wind turbine in series which allows you to achieve the required voltage and eliminate the DC to DC converter at the HVDC link side but the drawback with this topology is that wind turbine must be rated for higher voltage and over-rated when a turbine is out.

The author also performed a simulation of the DC collection grid under different fault conditions and isolation of the faults and the most suitable DC to DC topology for high voltage and high-power applications.

The following gaps were identified in this dissertation and the authors proposed this for future work

a. In this dissertation, a pi model of the cables was used which does not account for high frequency components. To achieve an improved model of the windfarm, a high frequency model of the cable should be used which will be able to improve upon the accuracy of high frequency model for internal faults and transients associated with it.
b. In this dissertation, it was proposed for future work for further research investigation in to the interaction of wind turbine and the DC to DC converter for an external grid fault.
c. For limitation in the power flow, the dissertation only explored the option of stopping the power flow, a gap identified is to explore the options of limiting the

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output power and research and investigate the interactions between the wind turbine and the DC to DC converter that will possibly create oscillations.

[Fujin Deng, *"Design and control of DC grid for offshore windfarm" Phd dissertation, Aalborg University, Denmark, 2012*]. The author of this dissertation indicated that the recently the DC collection grids interconnected with offshore wind turbines with DC output instead of AC output integrated to a DC collection bus has been an attractive area that has generated an interest in research. The proliferation of the DC grid technology provided a platform for interconnecting the wind turbine at the collection level making it feasible for DC grid to be realized. The author presented three topology layouts of the DC grid windfarm and discussed in detail some DC to DC converter topology and efficiency of each converter is evaluated.

The author presented three topologies of the DC grid windfarm that can be connected in radial configuration and the internal dc grid stringed together, the first topology has the DC to DC converter embedded or installed in the wind turbine which makes it possible to step up the DC link voltage to a medium voltage level. It is then integrated with an offshore main DC to DC converter which makes it possible to step up the voltage from a medium voltage to a higher voltage. The merit and advantage with this topology as stated by the author is that it allows the collection voltage to be set higher which will reduce the size of the DC cable compared with traditional ac cable at the collection level. It will also reduce the losses associated with the DC cable. The author stated that this topology layout also allows the internal dc bus to be controlled to achieve an improved performance and system reliability. In the second topology option proposed by the author, the internal DC to DC converter to the wind turbine is removed and only one main DC to DC converter is used. In this topology, the author argued that the collection voltage is the same as then DC link voltage which will impose a high current requirement in the DC cable. In the third option topology proposed, the main DC to DC

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converter is removed and only the internal DC to DC converter is kept and since this internal DC to DC converter is linked to then main DC transmission level, it imposes strong requirements for an enhanced design on the wind turbine.

The author also indicated for a DC grid system because they are connected by a cable when there is a cable fault, it becomes a permanent fault and will take a long time to clear the fault. A protection scheme was proposed by the author to include AC breakers to isolate the DC fault from the AC side, mechanical switches and DC breakers and chopper discharge resistors for discharging a DC link.

The paper also compared two types of generator side converter, the uncontrollable diode and VSC and concluded that though the uncontrollable diodes has a lower cost and lower switching losses it leads to a lot of harmonics which makes the VSC a much preferable generator side converter. The author asserted that the 3-level converter-NPC VSC is the best choice for the generator side converter and the Full bridge configuration is then best choice for the DC to DC converter and for the offshore HVDC the author concluded that the MMC VSC is the best choice based.

The following proposal for future work was presented by the author

- The author stated that an MMC topology or configuration should be used for the DC to DC converter to improve upon the power quality and efficiency and to do more research to come up with solutions to mitigate the over voltages at the DC link.
- The author indicated that another modulation strategy for the DC to DC converter need to be researched and a much robust control scheme needs to be implemented to maintain stability.
- The author stated that DC collection point and wind turbine fault needs to be researched and analysed.
- The author further asserted that protection scheme under DC fault still needs further research

- The author further asserted that the interaction of the wind turbine and the converters with the power system under DC faults needs to be researched, studied and analysed

A gap that was identified with this model is the failure of the author to utilize the high frequency model of the cable and there was no discussion on the filter configuration.

In [Antony James Beddard, *Phd Dissertation, University of Manchester, 2014*] the author asserted that the key challenge in the development of HVDC is the protection of the grid for DC faults and in the thesis a model of three nodes of 600MW, totalling 1800W was presented. The author further stated that the traditional approach to isolate DC faults when they occur is to block the converters at each end and the A.C breakers are tripped. The author indicated a DC grid fault could cause the disconnection of the generated power of 1.8GW but when DC breakers are implemented it will allow the faulty section to be isolated and dc faults cleared without the de-energizing the dc grid.

The realization of IGBT breakers and commercialization by manufacturer's like ABB and Siemen's has made the DC collection grid an achievable vision.

The authors presented a detailed technical literature and system description of different types of breakers that have been used in HVDC and the ones that can be employed in DC collection grid. They are

- Passive and Active Resonance DC circuit breaker which consist of an AC breaker and two parallel sections of resonant circuits containing L and C components. Under normal operations the line current flows the AC breaker and during faults conditions the AC breaker will open its contacts and create arc voltage which will increase and cause an increase in the arc length. This increased arc voltage will interact with the LC

parameters to provide current oscillation that will grow until it is equal and opposite to the line current which will provide zero crossing and the arc extinguished

- Hybrid Circuit Breakers which consist of a minimum of two sets of switches, one switch being a fast-mechanical switch and the other a solid-state thyristor switch. The drawback of this arrangement is the inability of the thyristor switch to turn off by itself. To improve upon the limitations of the initial hybrid circuit breaker, a hybrid commutation circuit which contains three branches in parallel (Mechanical switch plus solid state switch with turn off capability and surge arrester was used. Under normal operation the line current flows through the semi-conductor and mechanical switch and when there is a fault the switch opens and the commutation thyristor allows the commutation of the line current through another branch.
- Solid State breaker which is a DC breaker that consist of a string of anti-parallel semi-conductors. Under normal operations the current flows through the semi-conductor and when a fault is detected, the semi-conductor devices are turned off and any rapid voltage increase is mitigated by surge arresters
- Hybrid with forced commutation which has the capability to interrupt the fault current quicker than the conventional hybrid DC breaker which leads to a reduction in the interruption time
- IGBT Circuit Breakers has also been realized which is much faster

From this literature, the realization and commercialization of the fast IGBT DC breakers provides a research platform for it to be used in DC grid collection system, DC windfarm and various outline of the DC transmission system to provide an effective solution for isolating DC faults. It application will much be based on cost and efficiency analysis with other types of DC breakers

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RESEARCH SCOPE

The outline that is proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes or groups of aggregate model of total wind turbine generation source totalling 1800MW, 50Hz. The first node or group of generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 33kVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from 33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore. The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV dc grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV dc grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load and synchronous generation source rated at 1000MW, 60Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission

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converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to a step-up power transformer and main power system grid with a rating of 2800MW, 400KV, 50Hz.

The scope of this research is to take a different approach into the design of the most efficient DC windfarm topology compared with the traditional AC farm based on the analysis of transmission system losses, cost and utilization of realistic transmission cable distances, realization and commercialization of most components of the DC grid collection system.

The improved model will integrate to a hybrid HVDC main transmission converter.

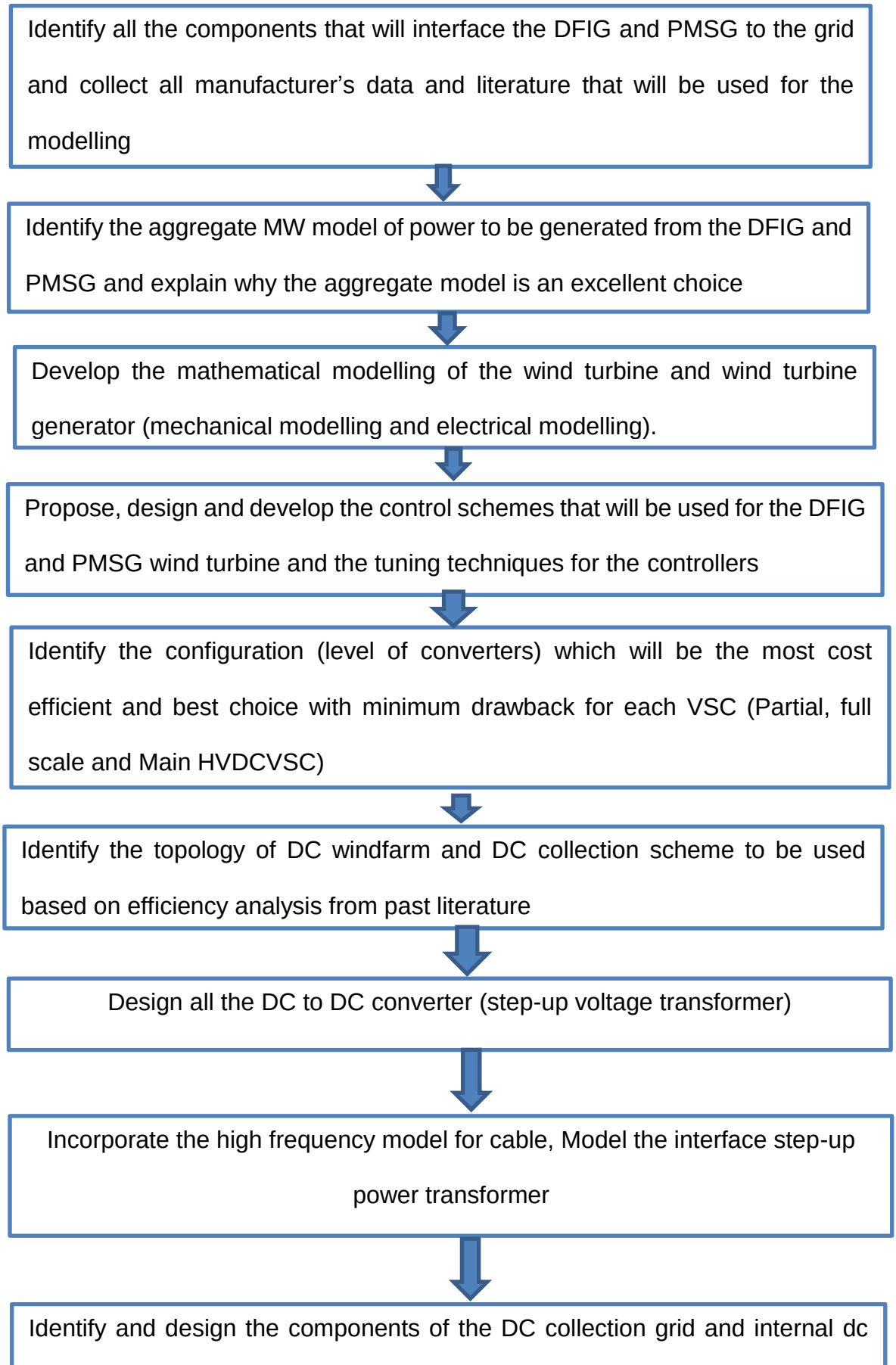
The research will take a different approach of proposing and implementing an improved model of the DC windfarm that will utilize high frequency model of the cable in the model and evaluate the response of the wind turbine and the interaction of the converters and the power system for internal and external faults and an improved model implemented to offer a robust protection system for DC faults.

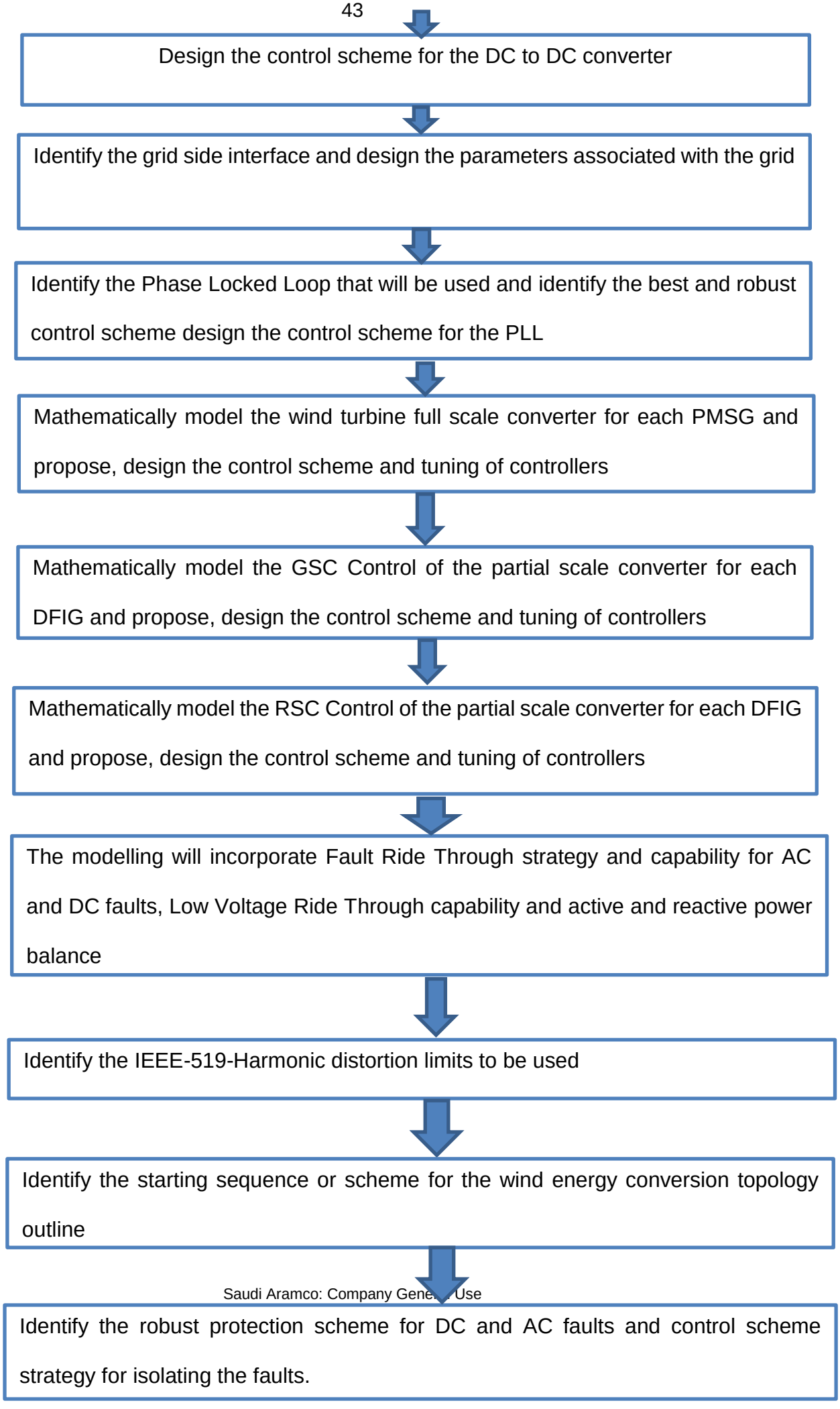
The improved model will also evaluate the presence of harmonics and resonance in the topology outline and the possible design of robust filters to mitigate these harmonics that will be present in the operation of the topology in figure 1 and test the response of the filters to unbalanced conditions.

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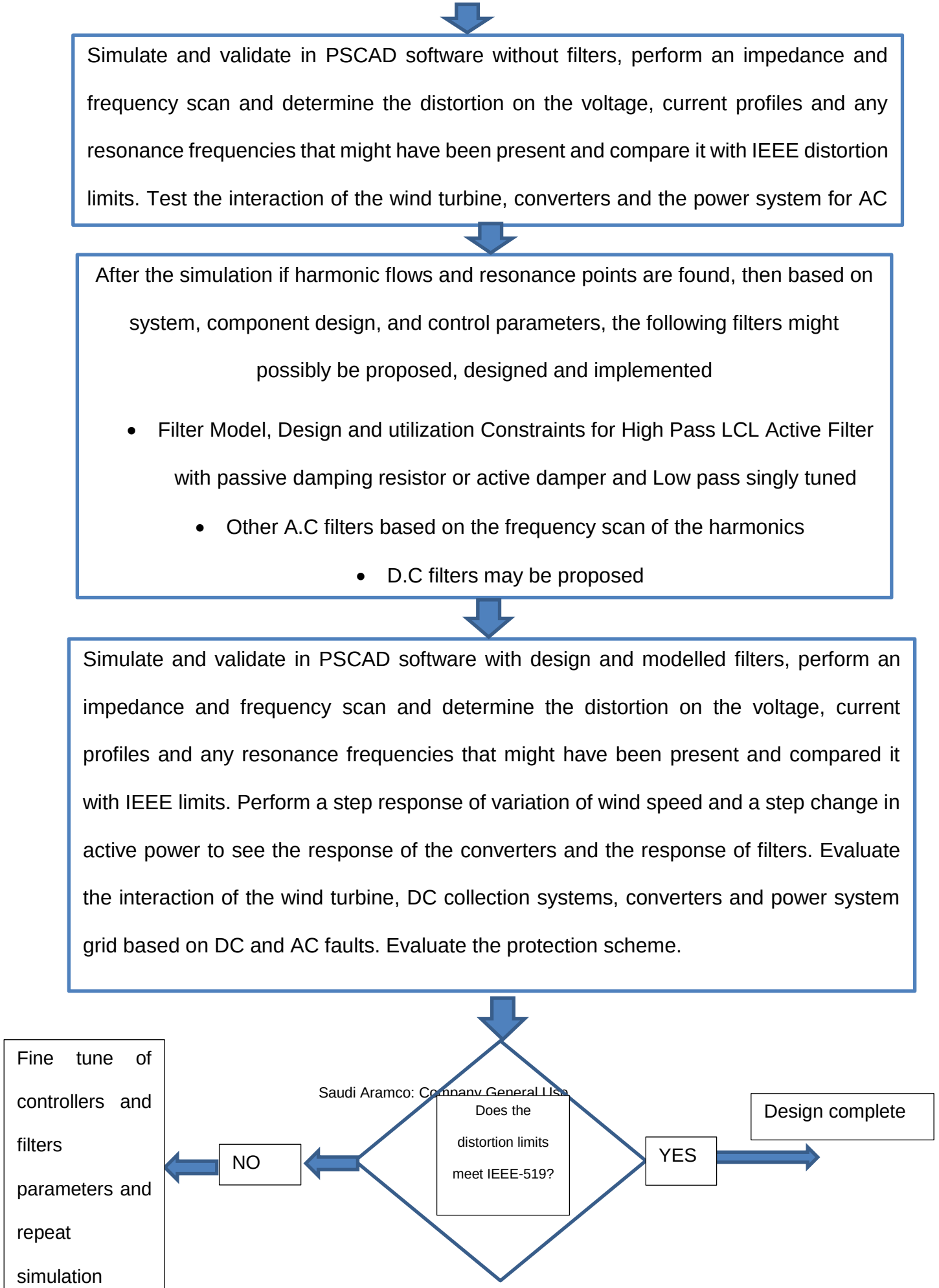
PROPOSED RESEARCH METHODOLOGY

Below is the research methodology





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TOPOLOGY OR OUTLINE OF THE PROPOSED DC WIND FARM AND DC GRID COLLECTION SYSTEM TO HYBRID HVDC AND THE MAIN GRID

Figure 1 below shows the system topology or schematic configuration of the Doubly Fed Induction Generator (DFIG) and PMSG that is integrated to DC collection grid system and Main Hybrid HVDC converter and the grid.

The outline that proposed in this research is shown in figure 1 of this proposal which consists of 3 nodes or groups of aggregate model of total wind turbine generation source totalling 1800MW, 50Hz. The first node or generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of 40 DFIG. The output of the DFIG AC windfarm is integrated to an internal AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 33kVac. The main AC collector bus is then integrated with a step-up power transformer which steps the output voltage from 33KVac to 115KV ac. The 115KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC VSC rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main DC collection grid bus all located offshore. The second aggregate of generation consist of 600MW of 3 sets of 40PMSG, each with an output of 5MW put into groups of 3 with 40PMSG in each group where DC wind farm layout has an output of 15KVdc and integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore, the entire outline integrated to a 150KV dc grid collector bus. The third aggregate of generation consist of a 600MW of 3 sets of 40PMSG each with an output of 5MW put into groups of 3 of 40PMSG in each group where DC wind farm layout has a wind turbine output 6KVdc integrated to two stages of main transmission DC to DC converters, the first stage of DC to DC converter rated at 6KVdc/30KVdc and the second stage of converter rated at 30KVdc/150KVdc, the entire outline integrated to a 150KV dc grid collector bus. The 150KVdc DC collector bus is connected to a 500-1000km of DC transmission cable from offshore to an onshore main transmission one terminal VSC which is connected to a tap load

and synchronous generation source rated at 1000MW, 60Hz. The grid side of the main VSC HVDC converter is then connected to a hybrid Main HVDC transmission converter which has the LCC HVDC converter on the rectifier side and the VSC on the inverter side integrated to a step-up power transformer and main power system grid with a rating of 2800MW, 400KV, 50Hz.

Front End (1st generation Node-600MW, 50Hz) of Wind DFIG-Partial Scale Voltage Sourced Converter

The front end of the DFIG will have a partial scale Voltage Sourced Converter. A variable speed turbine generator like the DFIG has the stator phase winding that is connected to the grid and the rotor is connected to a “back to back” converter through a slip ring. The converter is composed of a generator side and grid side converter and a dc link in between the converter. The control of the generator side converter allows the control of the speed, Torque of the DFIG and active part and reactive part of the stator terminals. The DFIG stator feeds active power into the grid and active power is fed into the rotor or out of the rotor to the grid depending on the operation of DFIG.

Front end of 2nd and 3rd Generation Node(PMSG)-600MW, 50Hz

The second set of generation-PMSG will have a full scale VSC and booster converter DC to DC converter installed in the enclosure of the wind turbine that will step up the voltage from lower medium voltage DC voltage to a higher DC voltage.

Proposed Aggregate of Wind Farm

The figure 1 below shows the proposed aggregated wind farm (DFIG) and PMSG that is integrated to the grid. A total of 120DFIG with an output of 600MW in 3 groups of 40DFIG and generation of 200MW. The AC output voltage of the DFIG will be 4.16KV and it will be stepped

up with a 3-winding transformer in each enclosure from 4.16KV to 33KV. The voltage is then step up from 33KV/115KV through a power transformer and integrated with a one terminal full scale VSC to form a DC transmission system to a 150KV DC bus. The second node of aggregate of generation will be an aggregate of 600MW a total of 3 sets of 40 PMSG that will have a full scale VSC converter rectifier and integrated with a booster DC to DC Converter to form an internal dc collection bus with an output of 15KVdc. This internal dc collection bus for each wind turbine is stringed together to form a generation side point of common coupling DC collection and integrated with a transmission level DC to DC converter to step up the voltage from 15KVdc/150KV to a 150KV dc collection bus. The 3rd generation node will be an aggregate of 600MW consisting of a total of 3 sets of 40 PMSG integrated to a full scale VSC integrated to a DC to DC converter with an output voltage of 6KVdc and integrated with the main dc transmission system to a 150KV offshore DC collection bus via two stages of DC to DC converter with rating 6KVdc/30KVdc and 30KVdc/150KVdc respectively.

The entire connection at the 150kvdc bus is connected to a Main transmission level one terminal inverter full scale VSC which has a synchronous generation source connected to it and a tap load. The full scale VSC is integrated with a Main Hybrid HVDC converter and step up transformer of 115KV/400KV.

Proposed Power Transformer

The proposed rating of the power transformers will only be 1st generation node of 120DFIG generation set will be 33KV/115KV. The proposed rating of the second power transformer which will be the main HVDC bulk power transformer that will be integrated to the grid is 115KV/400KV.

Proposed Synchronous Generation Source

There will be a synchronous generation source of 1000MW, 60Hz that will be integrated with the main HVDC transmission level full scale Voltage Source Converter.

Tap Load to full Scale Main HVDC VSC

There will be a tap load of 200MW that will provide remote power to loads

Internal AC Collection Voltage for DFIG

The AC collection voltage for the DFIG will be 4.16KV

Internal DC bus Collection Voltage for PMSG

The internal DC collection voltage for the PMSG will be 15KVdc for the first generation set and for the second generation set the internal DC collection voltage will be 6KVdc.

Proposed offshore Platform for DC Collection Grid and A.C power transformer

A proposed offshore platform substation will support the step-up power transformer with rating 33KV/115KV for the DFIG and AC collection system for the first set of DFIG. This step-up transformer will be located at a mezzanine level yet to be determined. It will also contain the full scale VSC HVDC transmission level converter for the first set of generation source that will convert the output AC voltage of the step-up transformer to DC voltage. The full scale VSC HVDC will be located at a mezzanine level yet to be determined.

The offshore platform will also contain the Main DC collection grid for all three generation sets which will contain the components of the DC substation (DC GIS, etc) and DC to DC Converter which is used as a step-up transformer.

Proposed AC Cable

For the first generation set, the proposed AC cable with standard rating around the nominal voltage of 4.16KV will interconnect each DFIG in each group to the internal AC common collector and from the AC common collector to the step-up power transformer 4.16KV/4.16KV/33KV located on the offshore platform substation.

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For the first generation set another proposed AC cable with standard rating around the nominal voltage of 34.5KV will connect from the secondary side of the step-up transformer internal to DFIG to a step-up power transformer with rating of 33KV/115KV and AC cable with rating 34.5KV from the high side of step-up transformer to the full-scale rating Voltage Sourced Converter.

Proposed DC Cable

For the first generation set of DFIG, proposed DC cable will connect from the rectifier-DC side of the full scale Main transmission VSC to the DC grid collection bus.

For the second generation set, the proposed DC cable will be from the output of each wind turbine to form an internal DC collection bus. Another cable will connect from the internal dc collection to a main DC collection point and from the DC collection point to the generation side of the DC to DC and another DC cable from the grid side of the DC to DC converter to the Main DC Collection grid located offshore.

From the Main DC collection grid located offshore there will be another DC cable feed which will be the main HVDC DC transmission feed from offshore undersea cable to onshore full scale Main VSC HVDC.

Main DC Grid Collector Bus

The DC collector bus shall have a rating of 150KV and will consist of Modular Pack and portable Gas Insulated Switchgear, DC breakers, and possibly DC filters and protection scheme

Proposed onshore substation platform

The proposed onshore substation platform shall consist of a full-scale Main transmission level Voltage sourced converter, Main HVDC hybrid scheme, step-up power transformer with rating 150KV/400KV.

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Proposed Transmission Line

The proposed Transmission line with rating 400KV will connect from the secondary high side of the step-up transformer to the grid. Distance about 500-100km

Proposed AC cable

Another proposed AC cable with standard rating around the nominal voltage of 150KV will connect from the Hybrid full-scale rating Voltage Sourced Converter Inverter to the primary side of the step power transformer with rating 115KV/400KV, all components located on the onshore substation platform and another 150KV AC cable will also connected from the full-scale Main VSC inverter to the Hybrid LCC converter.

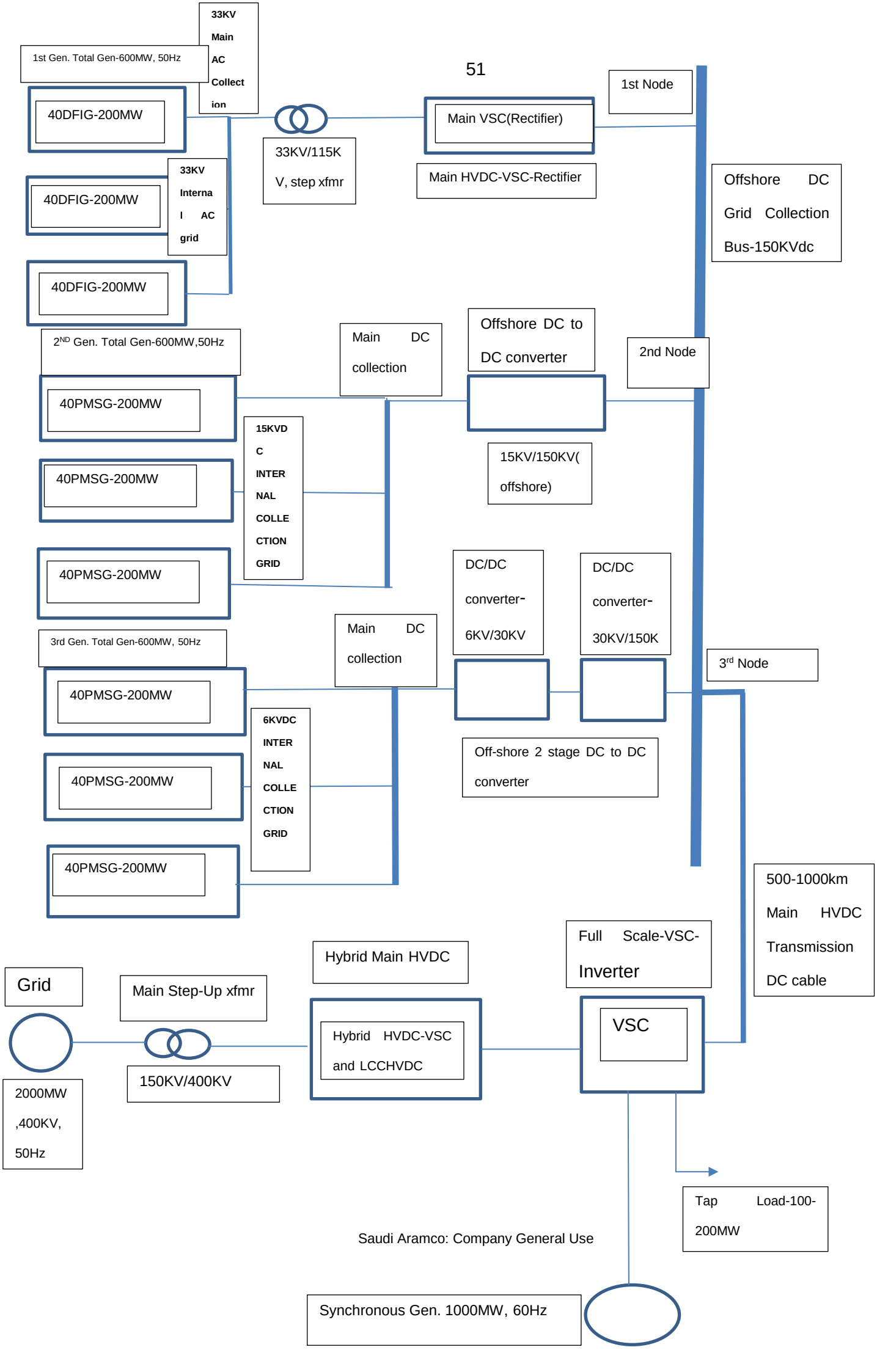
Proposed Main HVDC Hybrid Converter

The proposed Main HVDC Hybrid converter will be full scale rated MMC voltage sourced converter which is the inverter and the LCC HVDC which will be the rectifier.

Power System Grid

The power system grid will be rated at 2800MW,400KV,50Hz and other parameters will be determined in the design stage. A strong power system will be selected.

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