Voltage Control of Multi Terminal VSC-HVDC Transmission System For Offshore Wind Power Plant

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Abstract- *This paper deals with multiterminal voltage source converter (VSC) HVDC transmission systems for the connection of offshore wind power plants to the main land ac grid. A droop-based control scheme is considered. The droop controllers have been designed base on a mixed sensitivity criterion by solving a convex optimization problem with linear matrix inequalities. The system is analyzed by means of simulations and experimentally in a scaled platform. Simulations show the control performance during a wind speed change and a voltage sag in the main ac grid. Experimental results include wind power changes (increase and decrease) and an eventual VSC loss (both considering grid-side and wind farm VSC loss). In all the cases, the simulation and the experimental results have shown a good system performance.*

Keywords- voltage source inverter, cascade H bridge multilevel inverter, shunt active filter.

I. INTRODUCTION

Demand of electricity is ever increasing. Over the past decades, the increment in electricity demand has been largely balanced by capacity development of conventional generations. However, further capacity development of these generations to balance demand of electricity is considered unsustainable mainly due to limited resource of their primary energies and due to negative impacts they introduce to the environment. In order to meet the future demand of electricity as well as to replace ageing existing generations, a number of new generation technologies i.e. wind power, solar thermal, solar photovoltaic, biomass, biodiesel, tidal power and wave power, which make use of the renewable energy resources e.g. wind, solar, biomass, biodiesel, tidal and wave energy as their primary energy, have been developed.Wind power technology transforms kinetic energy in wind speed into electricity by utilizing a number of wind turbines. These wind turbines are installed in a particular area where the potency of wind energy is high and are linked together forming a wind power plant (WPP). In Europe, development of WPPs for electricity generation has been growing in past years and is expected to continue in the near future. At present, contribution of WPPs to electricity generation only covers a small percentage of the load. These WPPs are installed onshore and offshore close to the shore (less than 60 km). In the future, it is foreseen that a number of large capacity WPPs would be installed further offshore (more than 60 km) where high potency of wind energy and large space are available.

In order to integrate the future far offshore WPPs into the onshore grid, long cable transmission would be required. Moreover, regarding the capacity of these WPPs, large transmission capacity would be required. However, variability of the wind speed and thus variability of the power generated by WPPs would result in a relatively low capacity factor of the transmission and thus relatively high transmission cost per amount of energy delivered. The capacity factor can be increased if the transmission connects several offshore WPPs. Moreover, if the transmission is extended further, it may be used to facilitate power trading between countries in addition to evacuate power from the WPP. If these solutions were applied, several far offshore WPPs would be connected to multiple onshore grids and thus it would lead to the development of a transnational offshore network.For such a multi-terminal offshore network, where large power would be transmitted overlong distance, application of high-voltage alternating-current transmission (HVAC) technology may be difficult to implement due to large amount of reactive power compensation required. Thus, an alternative is to use high-voltage direct-current transmission (HVDC) technology. Moreover, since the offshore network may act as a power pool where power may be injected to and extracted from the network at different nodes, flexibility to control direction of power whilst maintaining voltage in the network is required. For such a situation, implementation of voltage sourced converter HVDC (VSC-HVDC) technology is favourable.

VSC-HVDC is capable of changing the direction of power whilst maintaining voltage in the dc network. Moreover, it is capable of performing independent active and reactive power control and of operating without necessarily depends on communication between the converters. Furthermore, since it is self commutated, it is inherently capable of providing self restoration as well as providing black start for the connected grid or the connected offshore installation. In addition, it introduces a compact converter station for offshore application due to the reactive power compensator is not necessarily required, and the amount of filters is reduced compared to line commutated converter HVDC (LCC-HVDC).Offshore wind power refers to the construction of wind farms in bodies of water to generate electricity from wind. Unlike the typical usage of the term "offshore" in the marine industry, offshore wind power includes inshore water areas such as lakes, fords and sheltered coastal areas, utilizing traditional fixed bottom wind turbine technologies, as well as deep water areas utilizing floating wind turbines. Wind farms are basically situated at such locations where abundant amount of wind is available. Mostly hilly areas or coastal areas are the most favorable sites for wind farm installation. These farms are called as onshore wind farms. The offshore wind farm is the one in which the wind turbines are situated in water far away from the land. Since wind flowing over the sea is high as compared to that of the land. Offshore wind farm has more potential winds than the onshore. The offshore wind turbine is stronger than onshore turbines and can last for 30 years.

It also produces approximately 50% more energy than the onshore. Whenever a strong wind blows it generates about 3-5 MW of power per hour. Since offshore wind farms are situated in water there is constant flow of wind for a long time which are stronger. The offshore wind turbines have different foundations depending on the depth of water in which they are placed. The various foundations are:

- Monopile - it consists of a steel pipe which is driven approximately about 32-64 ft into seabed.
- Gravity - it consists of a larger base which may be either made of concrete or steel resting on the seabed. The turbine of this foundation will be depend on the gravity for erection.
- Tripod - it relies on the technology used by oil & gas industries. The piles on each end are driven 34-60 ft in seabed. This foundation is used in deeper water. The other future foundations proposed for offshore wind farms in deep water are:
- lacket- a three legged platform able to be towed out to sea and lowered into place.
- Floating- it uses a tension-leg platform design which relies on a platform that floats below the surface of the water docked to the bottom with chains.

In the simulated model the wind farm is called as offshore since the speed of wind in offshore is always greater and consistent than onshore. Hence the speed has been fixed to 15m/s. The offshore wind farm is operating at 50 Hz frequency. It is connected through a step down transformer 13.8 KV/575KV.

Offshore wind farms present a number of benefits compared to traditional onshore wind farms. Namely, the availability of higher wind speed, the ease of transport of very large structures (allowing larger wind turbines), and the limited available inland locations to install new wind farms in some countries (mainly in Europe) render them a promising alternative. Thus, the number of offshore wind farms has grown in the recent years. Eight hundred sixty-six megawatt of offshore wind power was installed in Europe during 2011 (9% of the total new wind power installed in Europe). An important topic of discussion related to offshore wind generation is the transmission system. An offshore wind farm can be connected to the main ac grid using transmission systems based on ac or dc technology. The choice between these technologies depends on the cost of the installation which depends, in turn, on the transmission distance and power. The need to compensate for the impedance of the lines in ac transmission makes its price grow with the distance at a higher rate than dc transmission, whereas dc transmission implies a high fixed cost due to the need of large power converters.

Thus, there is a break-even distance from which the dc options become slower priced than ac. Until recently, HVDC, transmission systems were based on current-fed line-commutated converters.

New converter topologies and lower priced fast-switching semiconductors have recently made it possible to build voltage source converter (VSC)-based HVDC transmission systems. The benefits of using VSC and fast switching are the ability to independently control the active and reactive power while reducing the size of the output filters needed to have a low harmonic distortion .Most of the existing HVDC transmission systems use point to- point connections. This means that each individual wind farm converter is directly connected to the main ac grid by means of a dc cable. The opportunity to create new dc grids offshore, both interconnecting different countries and transmitting all the wind power generated, has risen the interest in converting point-to-point connections to meshed dc grids. The connection of different wind farms and different onshore ac grids can be performed with a common dc grid based in a multiterminal HVDC (M-HVDC) grid arrangement, where the terminals are wind farms or grid connections. M-HVDC grids present a number of challenges compared to point-to-point connections. One of the main obstacles to the development of dc grids offshore is the need for HVDC circuit breaker technology that is not commercially available yet. On the other hand, M-HVDC power balance and voltage control are a critical issue, particularly for the operation of the system under fault conditions. Different operation scenarios of an M-HVDC grid using droop control for decentralized voltage regulation were analyzed in . A droop design criterion based on steady state conditions is introduced in . The development of dynamic models of M-HVDC grids and a droop controller design methodology based on performance criteria. Regarding the offshore wind farm electrical topologies, some authors propose classical designs based on the common inland topologies as the double fed induction generators and the permanent magnet synchronous generators (PMSGs) with full-power converter (FPC), whereas some authors suggest to use fixed speed topologies such as the grid-connected squirrel cage induction generator (SCIG) and PMSG and to use the capabilities of the offshore wind farm converters to optimize the energy extraction of the turbines by changing the wind farm grid ac voltage and frequency.

II. PROBLEM DEFINITION

An important topic of discussion related to offshore wind generation is the transmission system. An offshore wind farm can be connected to the main ac grid using transmission systems based on ac or dc technology .The choice between these technologies depends on the cost of the installation which depends, in turn, on the transmission distance and power. The need to compensate for the impedance of the lines in ac transmission makes its price grow with the distance at a higher rate than dc transmission, whereas dc transmission implies a high fixed cost due to the need of large power converters. Thus, there is a break-even distance from which the dc options becomes lower priced than ac Until recently, HVDC, transmission systems were based on current-fed line-commutated converters. New converter topologies and lower priced fast-switching semiconductors have recently made it possible to build voltage source converter (VSC)-based HVDC transmission systems. The benefits of using VSC and fast switching are the ability to independently control the active and reactive power while reducing the size of the output filters needed to have a low harmonic distortion.

III. VSC-HVDCFUNDAMENTA CONCEPTS

A basic VSC-HVdc system comprises of two converter stations built with VSC topologies. Typically, many series-connected IGBTs are used for each semiconductor in order to deliver a higher blocking voltage capability for the converter, and therefore in-crease the dc bus voltage level of the HVdc system. It should be noted that an antiparallel diode is also needed in order to ensure the four-quadrant operation of the converter. The dc bus capacitor provides the required storage of the energy so that the power flow can be controlled and offers filtering for the dc harmonics. The VSC-HVdc system can also be built with other VSC topologies. Key topologies are presented in Section IV. The converter is typically controlled through sinusoidal PWM (SPWM), and the harmonics are directly associated with the switching frequency of each converter leg. Each phase leg of the converter is connected through a reactor to the ac system. Filters are also included on the ac side to furtherreduce the harmonic content flowing into the ac system.the relative location of the phasorsof the two ac sinusoidal quantities and their relationship throughthe voltage drop across the line reactor. One voltageis generated by the VSC and the other one is the voltage of theac system. At the fundamental frequency, the active and reactivepowers are defined by the following relationships, assuming thatthe reactor between the converter and the ac system is ideal (i.e.,lossless):

- Avoidance of commutation failures due to disturbances inthe ac network.
- Independent control of the reactive and active power consumed or generated by the converter.
- Possibility to connect the VSC-HVdc system to a “weak”ac network or even to one where no generation source is available, and naturally, the short-circuit level is very low.
- Faster dynamic response due to higher PWM than the fundamental switching frequency (phase-controlled) operation, which further results in reduced need for filtering,and hence smaller filter size.No need of transformers to assist the commutation processof the converter’s fully controlled semiconductors.

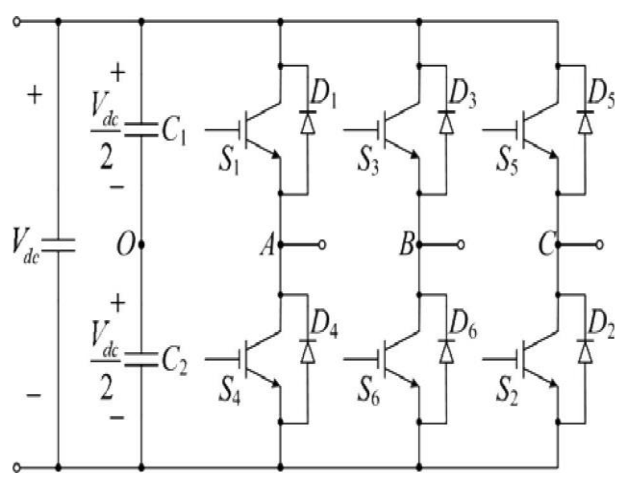


Fig No 1 Conventional three-phase two level VSC topology

3.2 VSC-HVDC Multilevel Topologies

In this section, different selected VSC topologies suitable for the implementation of a VSC-HVdc system are discussed. Multilevel converters extend the well-known advantages of low- and medium-power PWM converter technology into the high-power applications suitable for high-voltage high-power adjustable-speed drives and large converters for power systems through VSC-based FACTS and HVDC power transmission.

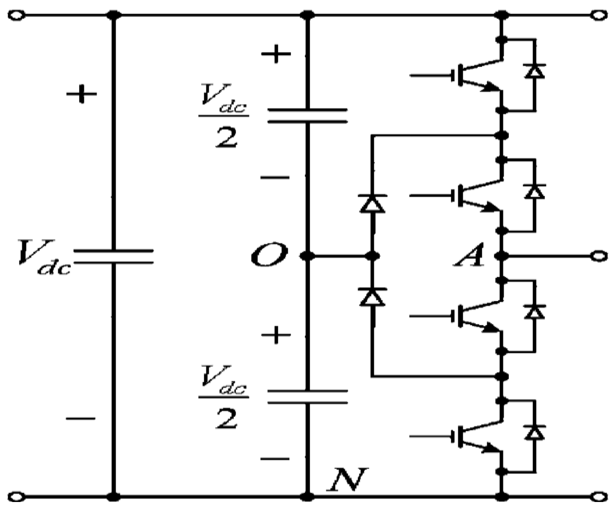
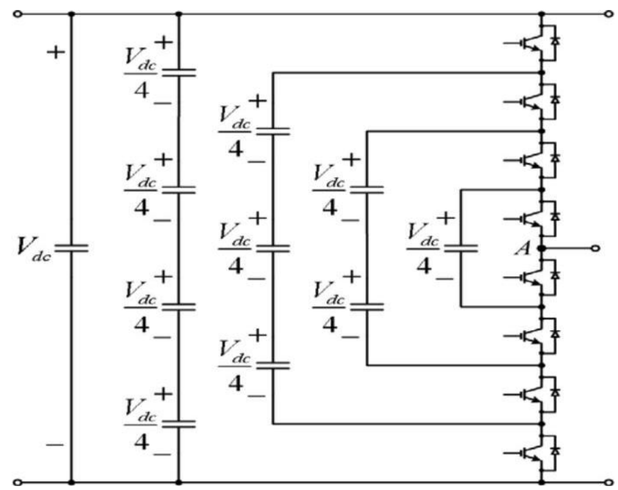


Fig. No 2. NPC phase leg.

There are numerous multilevel solid-state converter topologies reported in the technical literature. However, there are two distinct topologies, namely, the diode-clamped neutral point-clamped (NPC) converter (see Fig.1) and the flying capacitor (FC) converter (see Fig. 2). For clarity purposes, three-level and five-level PWM voltage waveforms on the line-to-neutral basis are shown in Figs. 3 and 4 ,respectively. Contributions for selected topologies that can be used to build an HVdc system were made in numerous technical papers. Specifically, PWM controlled HV dc concepts based on the three-phase two-level converter were reported using GTOs. A similar system was developed and reported using IGBTs and DSP control. Using modular approach and phase-shifted SPWM concepts, a number of advantages can be gained as far as the harmonic performance of the overall VSC-HV dc system is concerned. The diode-clamped NPC topology was studied in for an HV dc system in its three-level version(see Fig. 1). The benefits of using such a system were brought out; however, the converter has significant challenges with voltage balancing across the various dc bus capacitors, in addition to the uneven loss distribution between the devices. An actively clamped topology that is able to offer a solution to the loss distribution problem of the NPC was introduced in and is called active NPC (ANPC) converter. This topology is an attractive solution for HVdc applications.



FigNo 3. Five-level FC VSC phase leg.

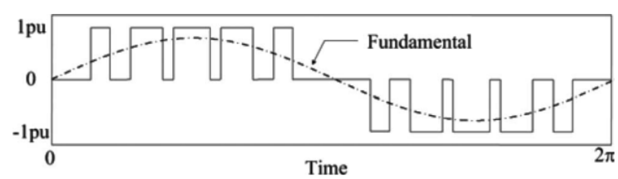


Fig.No 4 .Three-level PWM line-to-neutral voltage waveform.

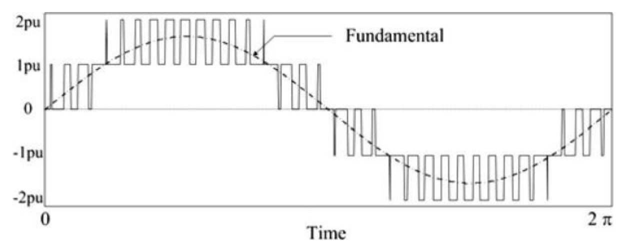


Fig.No 5.Five-level PWM line-to-neutral voltage waveform.

IV. CONTROL MODES FOR DIFFERENT CONVERTERS

In a typically configured MTDC system, there exist two kinds of converters: grid side converter (GSVSC) and wind farm side converter (WFVSC). GSVSC and WFVSC have different working modes, determined by the DC voltage and current.

A four terminal MTDC network is studied, as shown in Figure 6 On the left side of MTDC is the WFVSC integrating various wind farms, such as DIFG or full converter based induction generators. The duty for the WFVSC is to deliver all the possible wind power collected by the wind farm to the DC cable, meanwhile maintaining the AC side voltage or providing reactive power support if necessary. The GSVSC will try to control the DC voltage at a desired level, delivering the power out of the DC cable. Proper power transfer is indicated by the DC voltage. If the injected power is higher than delivered, the DC voltage will rise, otherwise it will fall. Thus for a MTDC network in normal operation, the basic tasks are to transfer power while maintaining the DC voltage.

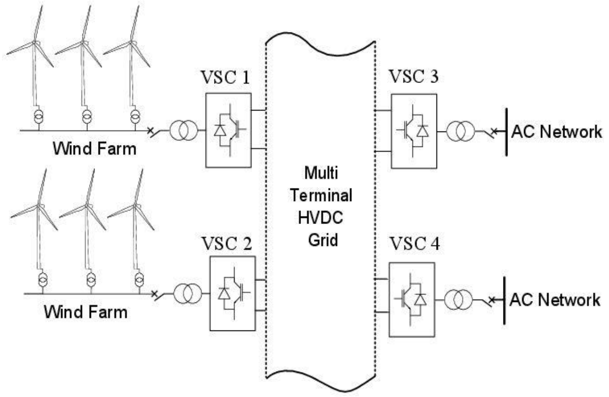


Fig No 6Typical four-terminal HVDC network

V. SYSTEM DESIGN

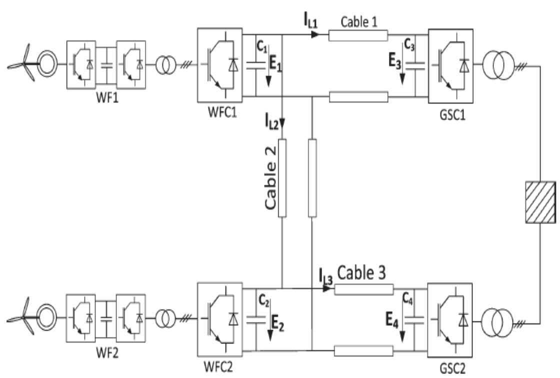


Fig No 7 Scheme of the simulated M-HVDC system.

5.1 Control Design

The control scheme consists of two control levels. The first level is the current control of each converter, which is achieved by using conventional flux-oriented control method . The second level is the dc voltage regulation which is achieved by using decentralized control strategy designed to allow proper transmission of the generated power from the WFCs to the GSCs while maintaining the voltage of the HVDC in a safe range of operation.

1) Current Control

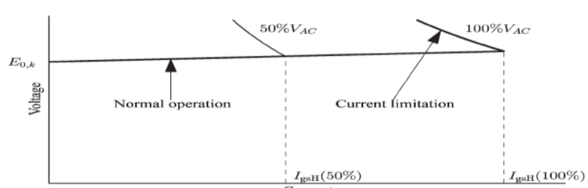


Fig No 8 Static current–voltage characteristic of a GSC. The thin line shows the characteristic under a voltage sag of 50%.

The current control is performed by changing the voltage applied by the converters on their ac side. In the case of the WFCs, a constant symmetrical three-phase voltage is applied to provide the voltage of the wind farm grid thus emulating the Thevenin equivalent of an ac network. Therefore, the current flowing through the WFC into the HVDC grid will depend on the power injected into the wind farm by its wind turbines. On the other hand, the control of the current in the GSCs is achieved by using a current control scheme which provides in dependent control of active and reactive power. The input of the current control loops is the reference value of the active and reactive power injected to the grid. The active power reference is calculated from $P^*_k = E_k I^*_k$, where $E_k$is the dc voltage at converter k and $I^*_k$is the reference value of the current flowing from the dc side of the converter according tothe droop control scheme.

5.1.2. Voltage Control

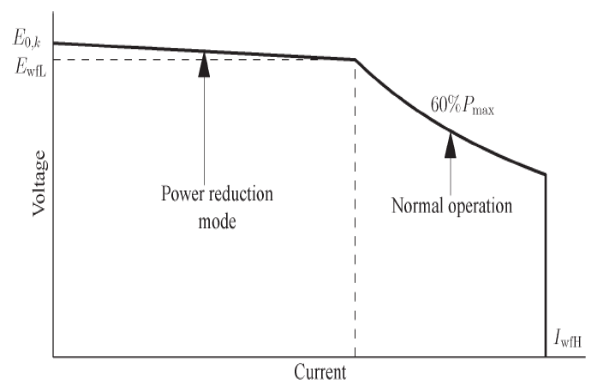


Fig.No 9 Static current–voltage characteristic of a WFC

The purpose of the voltage control is to ensure an adequate power transmission and it should be decentralized so that the control law applied by an HVDC converter only depends on local measurements made by that converter and does not need to rely on long distance communications between different terminals. The common formulation of this controller is the so-called droop control concept. The droop controller is a proportional control law that regulates the dc voltage and provides power sharing between the different power converters. During normal operation mode.

VI. SIMULATION RESULTS

The system under analysis is a M-HVDC transmission system with four terminals: two offshore wind farms and two onshore main ac grid connections. The two offshore wind farm VSC (WFC) power converters inject the power generated in each wind farm into the HVDC grid, whereas the grid-side VSC (GSC) power converters inject the power from the HVDC grid into the main ac grid. The HVDC grid consists of three submarine cables: Two of them connect each wind farm to an onshore VSC, while a third tie cable connects the two wind farms together in order to provide redundancy and share the power injected by each onshore converter.

The simulated system is an offshore M-HVDC transmission system fed by two wind farms equipped with FPC wind turbines. The simulated system is shown in Fig. 6.1. Three different scenarios have been considered: when load is reduced in the wind farms, when load is increased in the wind farms, and when wind farm1 is disconnected. For both control schemes, the current controllers have been tuned to achieve a time constant of 10 ms.The droop designed following the steady-state methodology has been designed to reach the nominal voltage under steady-state conditions when the system is transmitting the nominal power.

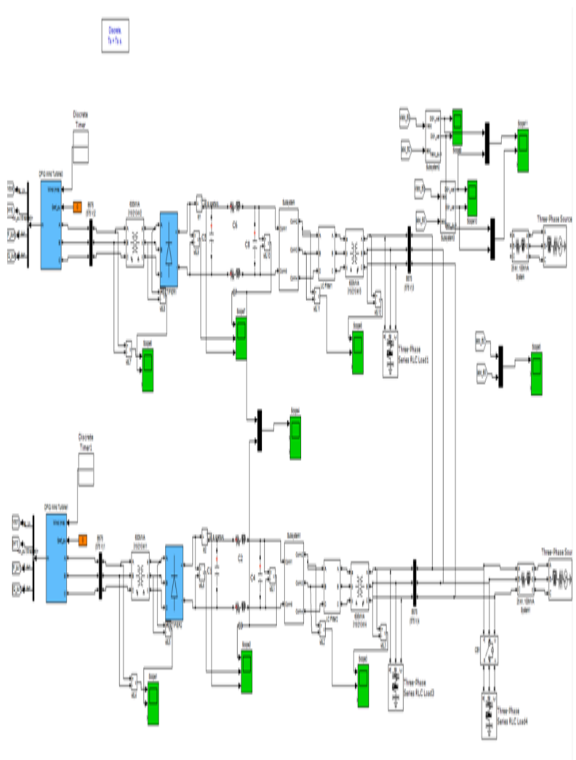


Fig No 10 Scheme Of The Simulated M-HVDC System.

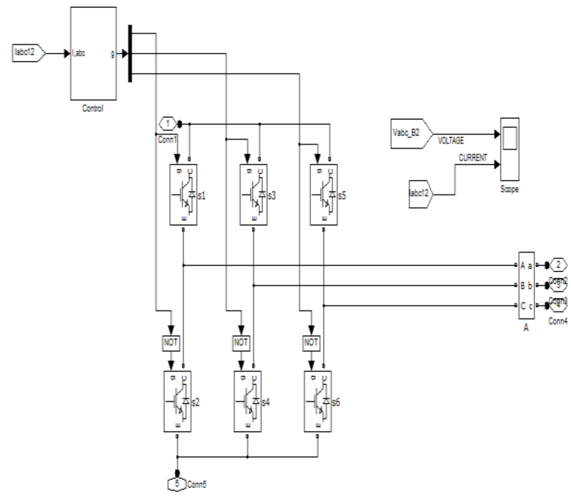


Fig No 11 Subsystem Model

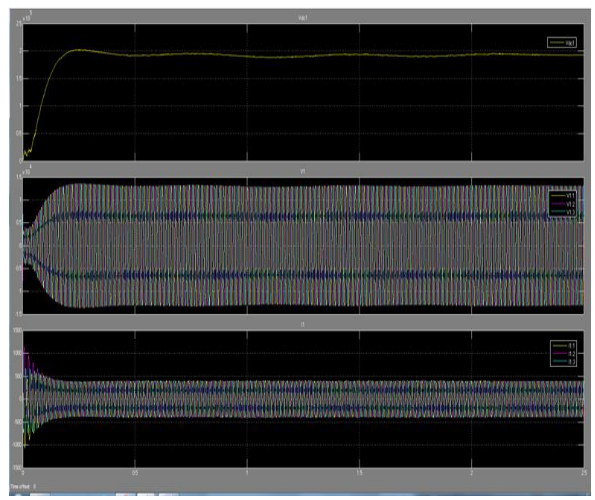


Fig No 12 During Normal Condition Voltage And Current Of Wind Farm1.

The purpose of the voltage control is to ensure an adequate power transmission and it should be decentralized so that the control law applied by an HVDC converter only depends on local measurements made by that converter and does not need to rely on long distance communications between different terminals. The common formulation of this controller is the so-called droop control concept . The droop controller is a proportional control law that regulates the dc voltage and provides power sharing between the different power converters. During normal operation mode, the WFCs inject all the generated current into the HVDC grid, while the GSCs maintain the dc voltage almost constant.

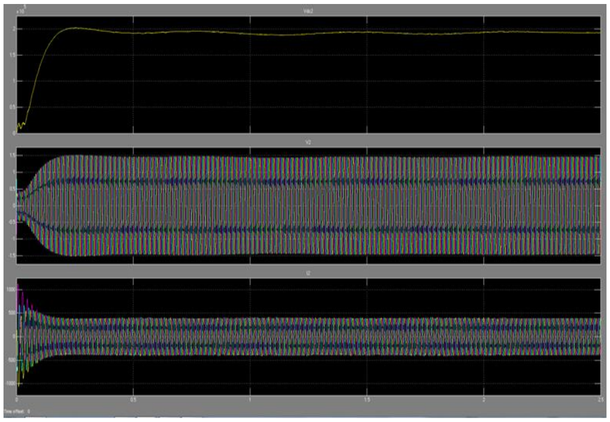


Fig No 13 During Normal Condition Voltage And Current Of Wind Farm2.

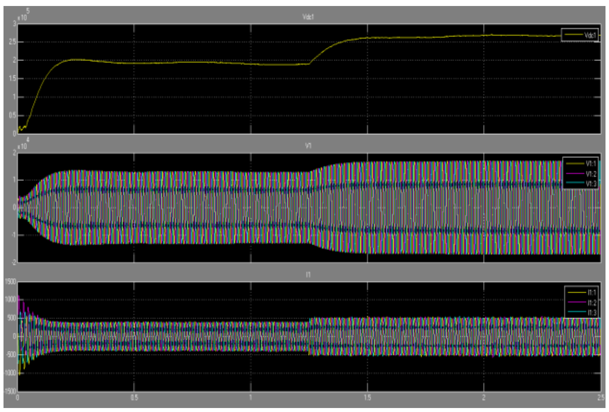


Fig No 14 When load is reduced from wind generator

In this case, the system is operating under normal conditions, and the HVDC grid is transmitting all the generated power. Figs. 14 show the voltage and the current of the system with a control designed with the proposed methodology and a steady state methodology. When the power increase starts at time instant t = 2s, in both cases, the voltage is increased according to the droop controller law to reach a new equilibrium point. Regarding the currents, when WF2 is increasing the generated power, and GSC1 and GSC2 are increasing also the injected power to the ac grid proportionally. The current injected by WF1 remains constant during all the time. In normal conditions, the major differences between both methods can be observed in the steady-state equilibrium point and not during the transient.

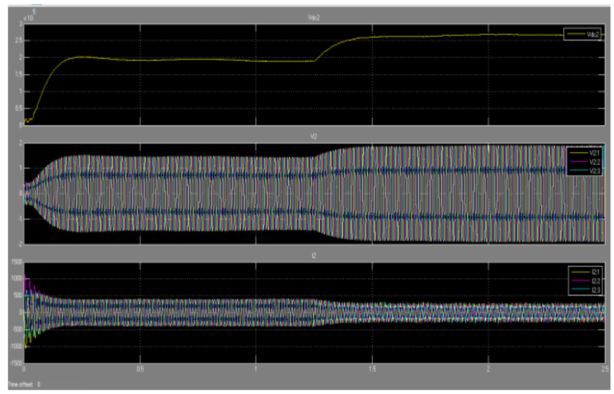


Fig No 15 Voltage and Current of Wind Farm1

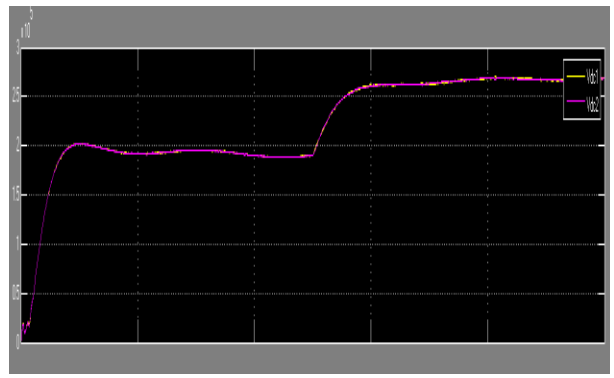


Fig No 16 Dc Voltage 1 and 2

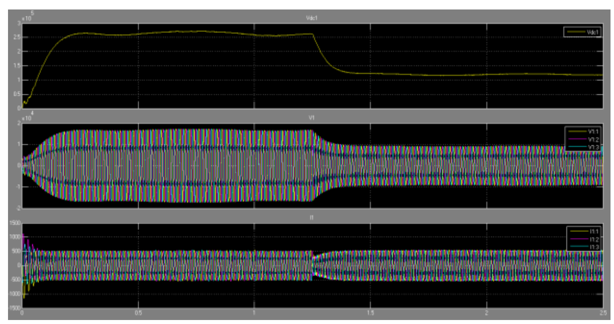


Fig No 17. when load is increased Voltage and Current of Wind Farm1

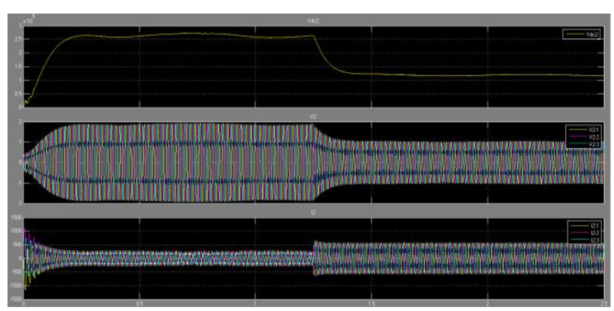


Fig No 18Voltage and Current of Wind Farm 2

In this case, the power in the WF2 changes, whereas the power in WF1 remains constant. In this situation, the multiterminal grid works in normal operation. During this operation mode, only the droop controls in both grid-side converters are active in order to regulate the dc voltages and ensure an adequate transmission of the power generated in the wind farms. Fig.16 shows the voltages and currents at each extreme of the experimental dc grid. It can be observed that the droop control is able to maintain the voltage within the range of 10% error with a highly damped behavior. As shown in Fig.16, the current in both GSC increases in the same proportion to extract the increase of the power coming from the WF2. The power at each node of the multi terminal dc grid and the ac currents of the GSC2 can be seen in Fig. 17. As the voltages remain almost constant during the power increase, the evolutions of the currents are similar to the current ones in Fig. 18.

VII. CONCLUSION

This Paper has addressed the operation and control of multiterminal VSC-HVDC transmission farms. A droop-based control scheme has been designed to ensure the dc grid voltage stability, wind farm power correct evacuation, and power sharing between the grid-side converters. The M-HVDC grid has been simulated considering a megawatt-range power system in three different case studies: when load is reduced in the wind farms, when load is increased in the wind farms, and when wind farm1 is disconnected. Simulations shows a the proposed droop design methodology. The effect of grid side DC voltage change on the transmission loss has been analysed. It is found that in order to achieve the minimal transmission loss the grid side DC voltage should be equal with an ideal constant current input from the wind farm side. However, when the wind farm side VSC works in constant power mode, this requirement will change due to the power characteristic of the wind farm power injection. Simulations have been carried out in Simulink and the analysis is verified by simulation results.

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