DYNAMIC ANALYSIS OF MARINE CURRENT FARM CONNECTED TO GRID

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I, **Satendra Kumar Singh Kushwaha**, Roll No. 2K13/PSY/17 student of **M. Tech. (Power System)**, hereby declare that the dissertation/project titled **"Dynamic Analysis of marine current farm"** under the supervision of Dr. S. T. Nagarajan, Assistant Professor, Department of Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

The power generation capacity of marine currents is enormous. Marine current power is recognized as a continuous available form of renewable resource witch can be used for sustainable generation of electricity. Due to high predictability and load factor marine current power it is more attractive for power generation and advantageous when compared to the other renewable energies where it is available. It can produce very huge amount of electrical power as compare to wind power due to density of water is thousands times the density of air. In recent years research in the area of marine current energy conversion has been carried out mostly in European countries such as Ireland.

The focus has been to develop a simple technology for converting the kinetic energy of oceans into electricity. The principle of converting kinetic energy of marine current into electrical energy is similar to the wind energy conversion technology. The concept is based on a marine current turbine (MCT) coupled with the induction generator that is designed based on the characteristics of the resource.

In this thesis stability aspect of MCT has been analysed during evacuation of power through conventional AC transmission line and HVDC line. It has been analysed that the power evacuation from MCT through conventional AC lines may have lesser stability limits in comparison with a parallel HVDC lines.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

MCT	Marine Current Turbine
MCF	Marine Current Farm
KEC	Kinetic Energy Converter
HVDC	High Voltage Direct Current
PCC	Point Of Common Coupling
LCC	Line Commutated Converter
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
AC	Alternating Current
DC	Direct Current
IG	Induction Generator
GB	Gear Box

CHAPTER 1

INTRODUCTION

1.1 Background

Oceans cover nearly two third surface of the earth and it has been considered as a vast renewable energy source for a very long time. The energy in oceans is stored in various forms. In recent years, several turbine technologies [1] have been developed for the capturing kinetic energy of oceans from tidal and marine currents. Tidal turbines and marine current turbines (MCT) have different designs [1]. Marine current turbine (MCT) works on similar principles to that of the wind turbines based on the fact that both of them have to capture the kinetic energy from the flowing mass of wind and marine current where powerful wind and marine current is available in geographical locations. The kinetic energy present in marine current can be converted into electrical energy with the help of MCT-generator technology [2]. The power density of marine-current energy is higher than the wind-turbine energy due to density of water is thousands times air therefore a large amount of electrical power generated in oceans can be supplied to the grid with MCT. Currently, in many countries ocean energy and wind energy have been connected together and feeding into power grid especially in the U.K. [3]. But, integration of ocean energy into a power grid face several challenges including maintain power quality, reduction of power fluctuations, connection of marine current farms to grids. To solve these mentioned obstacles, integration of marine power into a power grid, a HVDC link has been proposed in literature to integrate various farms of renewable energy to the grid [4]. Another advantage of HVDC link is that it can increase power transfer distance between offshore power generating stations to the load centres.

Already works have been started to tap marine current and supply power to grid [5] in this scenario it is worth to analysis the stability of marine current turbine systems for reliable power supply.

Few of work have been represented in literature regarding integration of marine current farm to grid. D. O. Sullivan et al. [6] have discussed the challenges associated with the grid interconnection of wave energy devices. Liambin XIE et al. [2] have proposed the modelling and control of PMSG based marine current power generation system. Li wang et al. [7] has performed the dynamic analysis of marine-current power generation system connected to a distribution system. S. E. Ben Elghali et al. [8] have proposed the modelling and control of a

DFIG based marine current turbine. Li wang et al. [9] analyses the comparative stability performance between VSC based HVDC Link and HVAC line interconnection of marine current farm to the grid. S. E. Ben Elghali et al. [10] compares the experimental validation of PMSG based marine current turbine and its control.

1.2 Marine Current Energy Resource

Marine current energy has a vast source of kinetic energy and great potentials for sustainable energy generation. It is a form of kinetic energy witch can be used for generation of electricity if a suitable methodology has been developed [11]. It is the one of the most continuous available farm of renewable energy that can be used to supply the base load. The resource potential for marine current farm is considered to be much larger than the other farm of renewable energy. In present scenario it is not widely used but it is a future of electricity. The research has been continued in this area to make more efficient, reliable and sustainable growth of marine current farm. It attracts the attention worldwide because of high predictability then wind and solar energy. The large flow of seawater due to wind and solar heating of the waters, although some ocean currents due to variation in density and salinity. Such currents are relatively constant flow and unidirectional, tidal currents are closer to the shore due to varying gravitational pull between sun and moon results in high tides. Some oceans current are the gulf steam, for example Florida straits current and California current. It transports water in huge amount through the Florida Straits. The Gulf Stream shown in Fig. 1.1 is generally 100 kilometres wide and 800 to 1200 metres deep. The velocity of Gulf Steam is faster near to the onshore with the maximum speed about 2.5 metres per second.

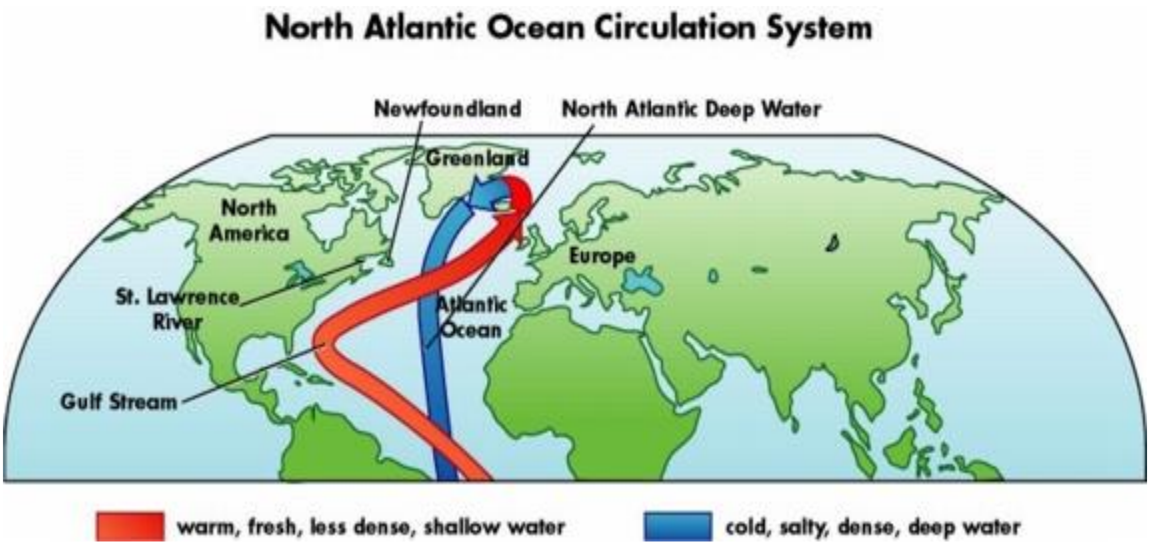


Fig 1.1 Gulf Steam in north Atlantic-oceans

In the southern part of Florida the straits current is 8km off-shore with large speed over a significant distance with unchanging pattern gives a site for installation of marine current power generation project. Marine current project concentrated at the site with significant current continues at the depth of the sea, it consider for clean power generation.

The gross kinetic energy of marine currents is extremely large and highly predictable. Although, the speed of marine current is generally lower than wind speeds, it carry the large amount of energy as compare to the wind energy because of the density of water. The density of water is thousands times the density of air, so for the same surface area and diameter of turbine water moving 12 miles per hour (mph) exerts approximately the same amount of power as a wind moves with constant speed of 110 mph. it is a unique farm of renewable energy, that is relatively independent of weather conditions. For successful utilization of this resource, proper methodology and understanding of the performance of hydrodynamics energy converter systems is essential.

1.3 Marine Energy Extraction System

There are several techniques for the extraction of energy from the oceans. The two most sustainable techniques for the extraction of energy from the oceans are kinetic energy conversion (KEC) system and ocean thermal energy conversion (OTEC) systems. OTEC uses the temperature difference between warm surface water of ocean and cooler deep water to run heat engine to produce electricity. However the temperature difference is small so that efficiency of power generation is low and production of electricity is small but OTEC is one of the most continuous available farms of renewable energy resource.

The kinetic Energy Conversion (KEC) system harness the kinetic energy of flowing water or marine current with the help of marine current turbine. Marine current turbine is driven by the massive flow of marine water inside the sea that’s rotate the MCT which is use as a prime-mover for the generator it convert the kinetic energy of the ocean current into electrical energy. The marine current turbine works on the similar principle to the wind turbines both turbines harness the kinetic energy of flowing mass and convert into rotational farm the generator convert rotational energy into electrical energy. These two kinetic energy conversion devices are use horizontal axis turbines [12-13] and vertical axis turbines for conversion of electricity. However the land based kinetic energy conversion devices facing a problem associated with the land use, thus the ocean offers a large space for implementing the new energy technologies on large scales with clean electrical energy generation and less impact on the environment or on human activities.

In recent few years, so many project on off-shore marine current power generation and it's interconnection with grid put in operation or under development in European countries namely Ire-land [14], (UK). A large scale extraction of marine energy through marine current turbine connected to grid is shown in Fig. 1.2 has been installed at Northern Ire-land UK in April 2008.

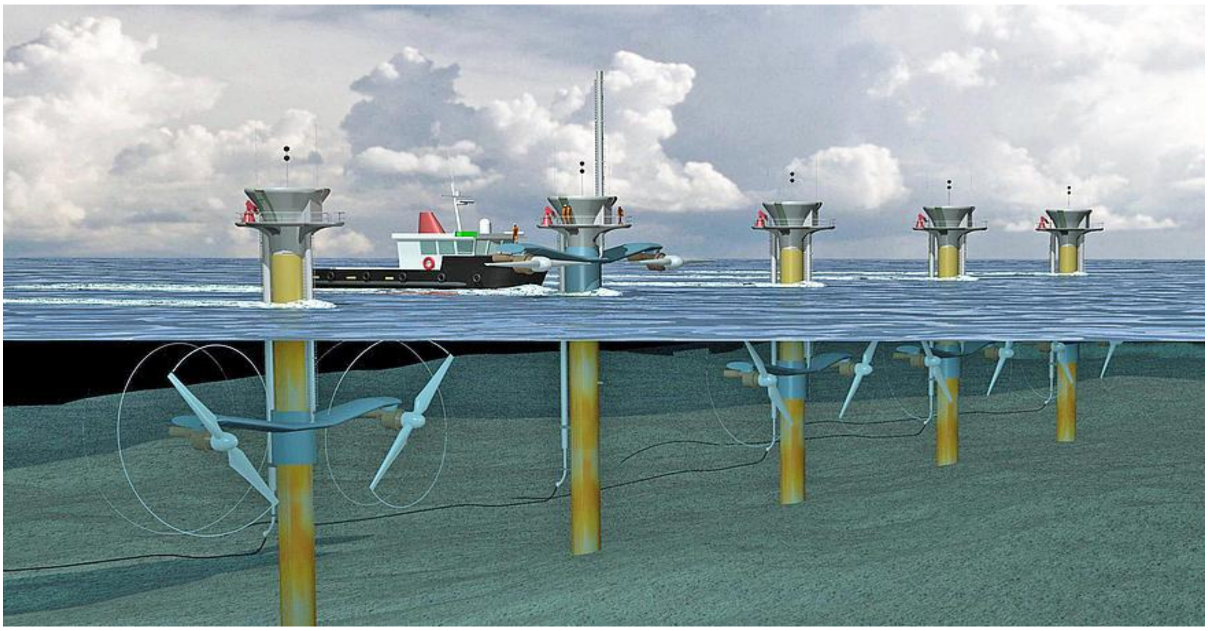


Fig. 1.2 Extraction of marine energy with the help of MCT (Courtesy of Marine Current Turbines (MCT) Ltd.)

In India the generation of electricity mainly by the conventional method such as thermal power plant but the research has been continued to make the renewable energy more reliable and efficient. Fig. 1.3 shows the power generation in India.

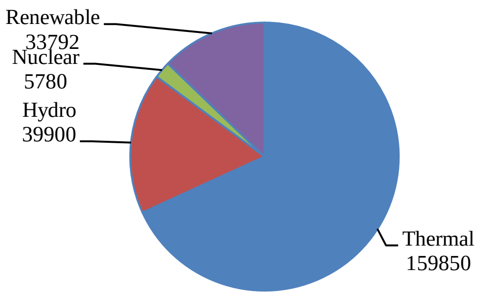


Fig. 1.3 Power generations in India

CHAPTER 2

MARINE CURRENT POWER GENERATION

2.1 Marine Current Power Generation Principles

The concept of marine current energy conversion system is different from the conventional hydro-power generation system. In conventional hydro-power generation system the amount of power generation depends on the height between the reservoir and the water level at bottom of the dam. Water falls from the head drive the turbine to rotate the generator, turbine use as a prime-mover, a similar approach has been used for tidal power generation. Power can be generate with high tides. A barrage has been constructed in a narrow bay for harnessing the potential energy high tides it use the head between high and low water.

Another method of generation of electricity from the water is to convert the kinetic energy of oceans current [15-16] or flowing water into the electrical energy with the help of marine current turbine. It is similar principle to the wind turbine which converts kinetic energy of wind into the electrical energy. The advantage of this technology is no need of dam or reservoir.

2.2 Marine Energy Extraction Technologies

Flowing water offers an analogous energy resource to the wind energy resource. The kinetic energy of moving fluid or marine current extracted on similar principle of wind energy with a suitable marine current turbine. The power available from a marine current is

$$P_m = \frac{1}{2}\rho_w A_{mct} V_m^3 C_p(\lambda, \vartheta) \tag{2.1}$$

Where P_m is the power extracted by marine current turbine, ρ_w is water density, A_{mct} is the cross-sectional area of the marine turbine and V_m is the free-stream velocity of the flowing mass or marine current and c_p is the power coefficient of marine current turbine, it's value depends on the turbine blade structure and hydrodynamics. Power coefficient c_p is a function of tip ratio and blade pitch angle ϑ. The value of c_p for normal operation is estimated approximately in the range of 0.35 to 0.5, the curve of c_p v/s tip speed ratio (TSR) is shown in Fig 2.1 base on the measurement of a three blade system [17-18]. Fig. 2.3 shows the MCT extractable powers at various turbine speed, which has been calculated based on the power coefficient curve (C_p) and the equation (2.1).

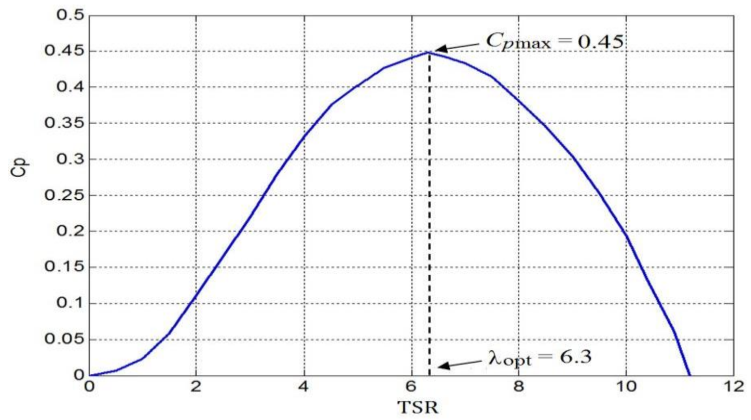


Fig 2.1 Cp curve of the MCT

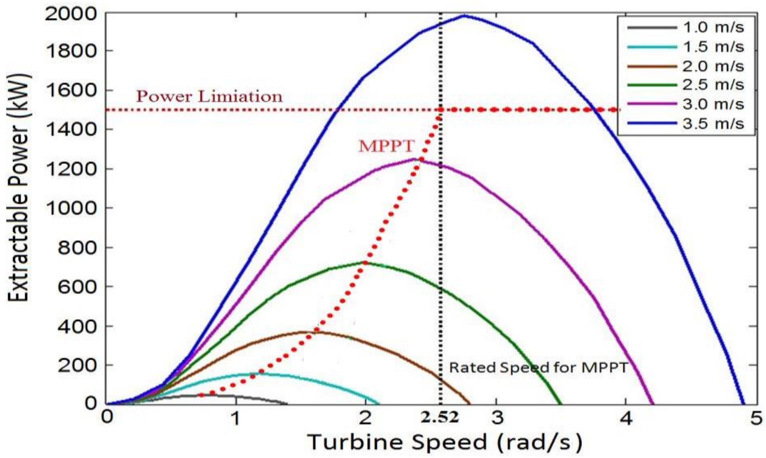


Fig 2.2 The MCT power characteristics

From the equation 2.1 it shows that the energy captured is highly sensitive to the velocity of flowing mass. Table 2.1 shows the power density for various water (marine current) velocities, compare with wind and solar resources.

Table 2.1 Relative power density of marine currents compared with wind and solar resources

Energy resource	Marine current					Wind	Solar
Velocity(m/s)	1	1.5	2	2.5	3	13	Peak
Velocity(knots)	1.9	2.9	3.9	4.9	5.8	25.3	Noon
Power density (kw/m^2)	0.52	1.74	4.12	8.05	13.91	1.37	≈1.0

It can be seen from the Table 2.1 that the marine current power with speed exceeding 2 m/s is produce high power density renewable energy resource compare with other farm of renewable energy resource it is a one of the best alternative of energy resource in future. The typical rated velocity of wind is 13 m/s. marine current turbine produce mush more power with less turbine speed or marine current due to the density of water, this is the reason why marine current turbine technology is commercially competitive.

The engineering approach to adopted and developed the technology for the conversion of kinetic energy of marine current in efficient manner and less capital cost since its fallow the principle similar to wind turbine but the challenges facing in marine current power generation is different than wind turbine power generation and more complex. There are two types of kinetic energy conversion device or two types of marine current turbines basically it's a constructional difference between them and axis of rotation. One is known as horizontal axis turbine [19-20] (fig 2.3) or propeller type rotor it driven by conventional axial flow and other one is vertical axis turbine (fig 2.4) also known as darrieus turbine it driven by cross flow.

Generally the horizontal axis marine current turbine has been consisting of two blade and 180 degree of blade angle control with diameter of 6 to 30 meter. For the controlling the power of marine current power or thrust blade angle with full span has been used and blade angle also make the marine current turbine bi-directional rotation for the flow of both the direction. The vertical axis marine current turbine consisting generally three blade system for its operation its blade angle controls the power of turbine or thrust of marine current and it maintained the power to not exceed the rating of the machine because the power flow mare then its rating can be damage the machine or cause of insulation brake-down of generator or connecting cables.

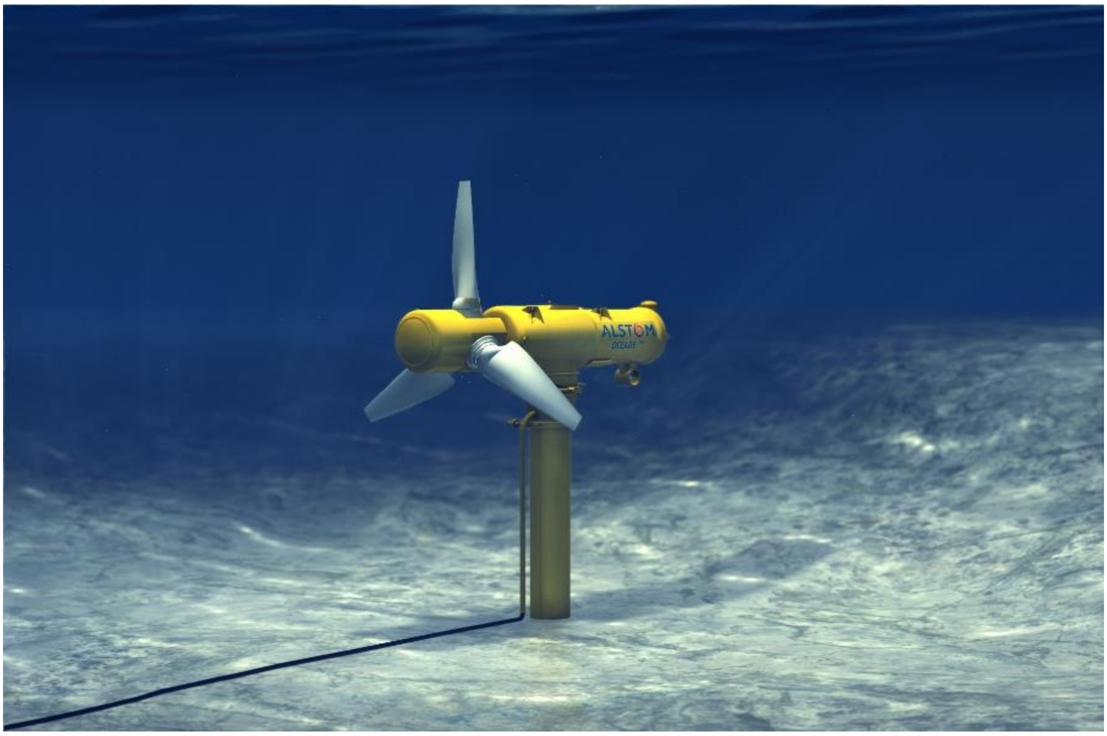


Fig. 2.3 Horizontal Axis Marine-Current Turbine Model

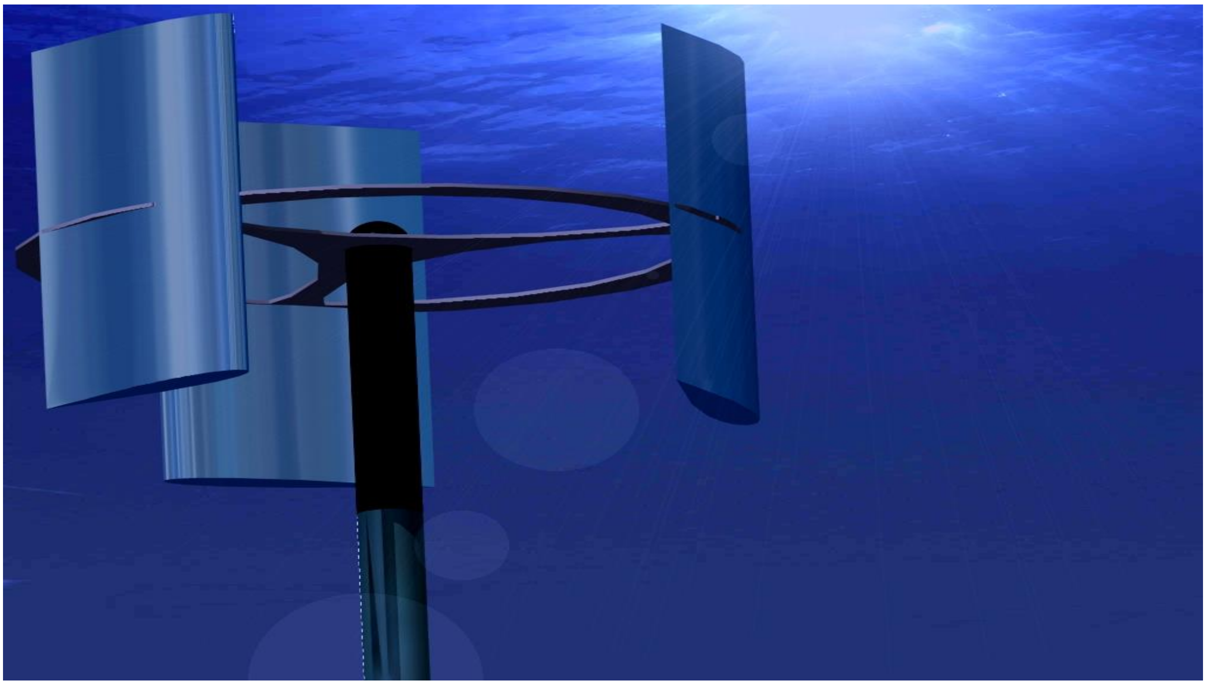


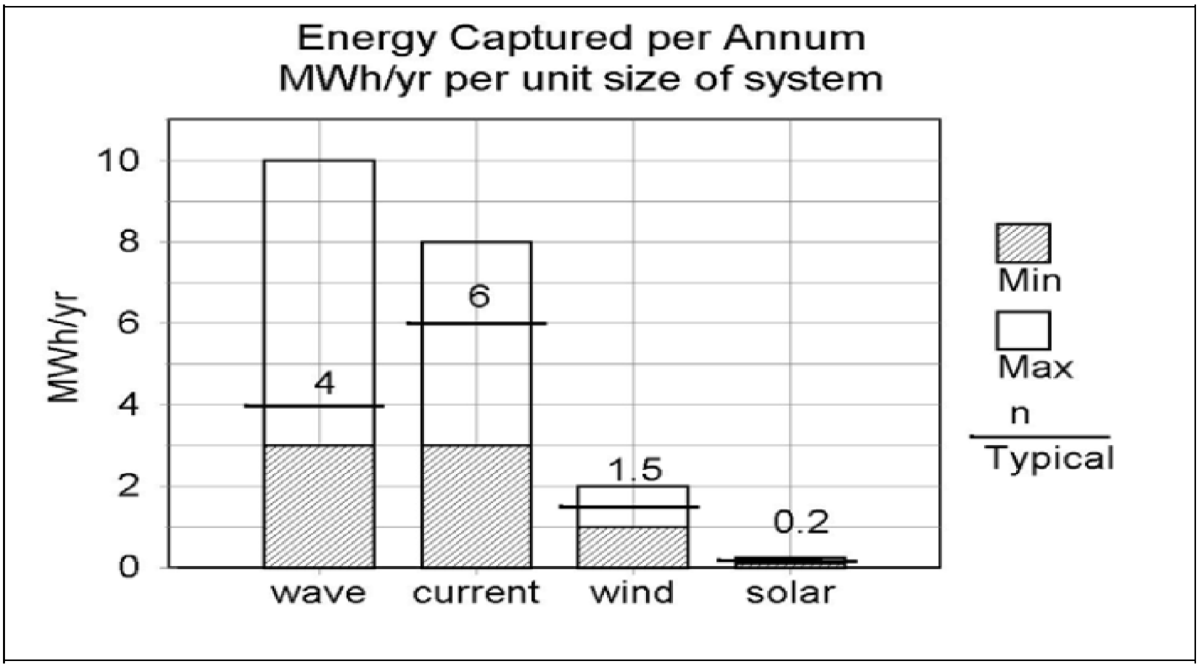
Fig 2.4 Vertical Axis Marine Current Turbine model (Source: www.esru.strath.ac.uk)

Both type of turbine has been fixed blade type and variable pitch angle blades [21-22]. Generally horizontal axis turbine has been used in marine current power generation system for extraction of energy from axil flow of water. This is a new technology of energy conversion No published standards are available. In addition, the technology is not mature, new variety, and sometimes uncommon designs are developed and tested. At this stage of development of technology it is not possible to give full description and wide range of technical data.

There is no standard for all aspects of marine current energy conversion system exist. Although marine current energy conversion system is a unique and novel technique for renewable energy conversion, the ability of extraction of power is more than the other farm of renewable energy.

In Table 2.2 shows the energy captured per annum per unit size of system. From this table it has been analysis that the generation of electricity from the marine current turbine is much more than the other renewable resource such as wind turbine for the same per unit size of turbine or machine. For same amount of generation of electricity per unit size of the marine current turbine is very small as compare to the wind energy turbine.

Table 2.2 Energy Captured per annum Mwh/yr per unit size of system



2.3 Marine Current Power Generation System in Operation or Under Development

In recent years, the development of marine current energy has been gone through a boost with several prototypes has been tested in real coastal sites. The testing of prototype helps to understand and improve to work in realistic operating conditions. The development of marine current power generation technology is proposed all over the world in coastal areas, around (≈300-700) MW in the Korean waters, Paimpol-Behat, France (≈4.0 MW), West Bengal, India (≈4.0 MW), Anglesey, UK (≈80.0 MW), the Bay of Fundy, Canada (≈6.0 MW), and Pouto, New Zealand (≈200 MW). In US and Australia the projects are under development. The projected duration for development of marine current power project is 5 to 10 years. They proposed to use horizontal axis marine current turbine. Although vertical axis turbine capture more energy but horizontal axis turbines is more effective in capturing the energy (ISSC Committee V.4, 2009) of marine current for a given swept area. Currently two projects SeaFlow and SeaGen has been successfully developed and installed by marine current turbines Ltd.

2.3.1 SEAFLOW

SEAFLOW has been world's first commercial size offshore marine current project for generation of electricity from the kinetic energy of marine current. It is installed in foreland point, on the North Devon coast England in 2003 has been successfully tested and operated since then.

SeaFlow's project shown in Fig. 2.5 is a single rotor horizontal axis marine current turbine consisting of two blades rotor of 12 meter diameter its rated power is a 300 kW, in a current speed of 2.7m/s with a hydrodynamic conversion efficiency of 40 present. The rotor made of composite material mounted on steel pile coupled with a generator through gearbox the whole system in the seabed can be slide up and down on the pile and slide above the sea surface for the maintenance purposes. The turbine has a full blade angle pitch control and it is capable of generating power for both directions of flow.

Fig. 2.5 SeaFlow rotor (Courtesy of Marine Current Turbines (MCT) Ltd.).

2.3.2 SEAGEN

SeaGen has been installed in Strangford Narrows, Northern Ireland UK in April 2008. It is the world's first large scale power generation plant of marine current. It is most powerful marine current turbine in world consisting of twin rotor has two blades each with 16 meter diameter. Each rotor sweeping the area of 200 square meters of flow producing an output power of 1.2 mw at marine current speed of 2.4 m/s. SeaGen uses axial flow full pitched controlled rotor through 180 degree allowing them to operate in both directions of flow.

SeaGen's rotors has been achieved around 48% efficiency over a wide range of oceanic current velocities and the turbines offer full control over the machine it can be shut down within three or four sec if required even with the full current flow.

Fig. 2.6 SeaGen twin rotor MCT (MCT, 2010)

In fig 2.6 shows a prototype Sea-Gen twin rotor marine current turbine technology developed by marine current turbine Ltd. Twin rotor on same pile produce a twice the power per pole at significantly less cost. This technology has been patent featured by marine current turbine Ltd with the rotor blades pitched 180 degree in order to operate in bi-direction.

SeaGen is the first large scale grid connected machine current power generator for commercial use ever in the industry of marine energy (Marine Current Turbines Ltd.).

2.4 Grid interconnection of marine current farm

As for the integration of marine current farm into the grid, one of the most advantage of marine energy is that it extract much more power than the other farm of renewable energy. Although marine current is quit complex and site specific but it is more reliable farm of renewable energy. This is the key factor of interconnection [23-24] of marine current energy to the supply network and future development of marine current energy. Connection of marine current power to the grid in two ways

i- Using conventional AC line

ii- Using HVDC Link between the generator and grid

The conventional AC transmission line has been use for the interconnection of marine current generator is quite simple less cost as compare to the HVDC link [25-26] but the AC line provide a synchronous connection between the generator so the if any frequency disturbance occurred at generator side or harmonics has been produced by generator by variable speed of marine current affect the grid or create stability problem to the grid. Integration of marine current power to the Grid using conventional AC line has been shown in fig 2.7

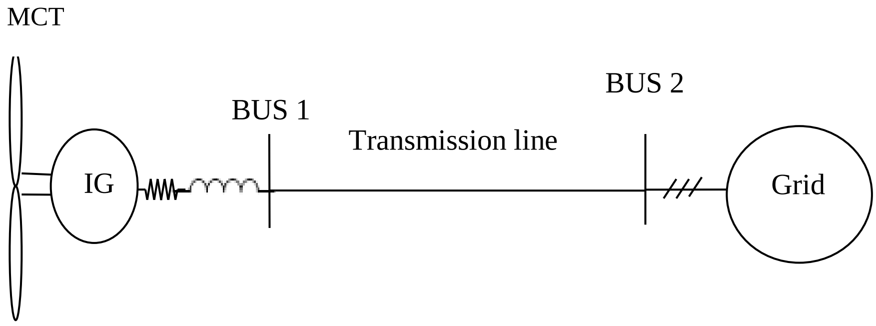


Fig 2.7 grid connection of MCF using conventional AC line

The interconnection of marine current generator to the grid by HVDC [25-26] Link is quite complex and higher cost as compare to the conventional AC transmission line but the HVDC Links gives advantage over AC line, HVDC Link provide an asynchronous Link between the generator and Grid so any disturbance occurred in generator or harmonics has been produced in generator side the effect on Grid side is significantly reduced with the help of HVDC Link. So HVDC Link increases the stability of the system [27-29]. The integration of marine current power to the grid using HVDC Link has been shown in fig 2.8 where bus 1 is the generator bus and bus 2 is grid side bus.

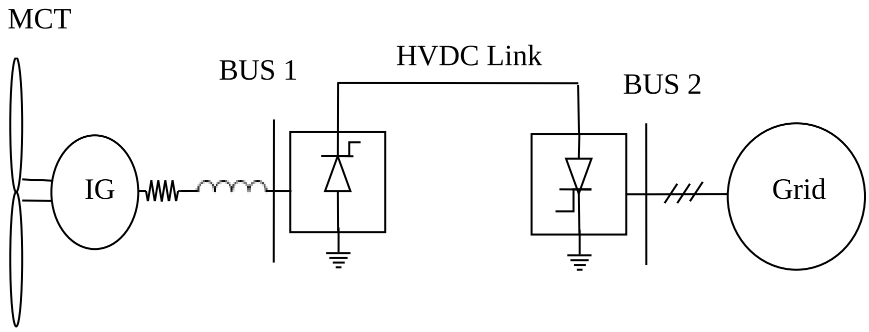


Fig 2.8 Grid connection of MCF using HVDC Link

2.4.1 Challenges in Grid Connection of Marine Current Farm

The integration of marine current energy into a national grid facing a different challenge to the interconnection [30-32] of other farm of renewable energy such as onshore wind, solar hydroelectricity etc. most of the renewable energy are on small scale and connected to the local supply or domestic load. They are not grid connected due to the high cost in grid connection. The development of onshore marine current turbine technology has been gradually moved towards the large scale integration of marine energy this development curve is relatively increased. In this scenario the integration of marine energy into national grid is a crucial factor and it can solve the shortage of power or increment in demand of power. In this considering the grid integration of large scale of marine energy conversion devices facing various technical and non-technical challenges that's need to short-out by marine energy device developers. The challenges are divided into two parts, generator side challenges and Grid side challenges.

2.4.2 Generators Side Challenge

The selection of a generator type for the marine energy conversion is an important issue that involves several factors [33]. It includes generator efficiency, generator reliability, environmental impact and cost of generator as well as grid connection suitability. The marine current generator is typically a rotating electrical machine which is either connected to the grid by conventional ac line or through HVDC Link. In conventional fossil fuel based generation plant synchronous generator has been used in the similar manner to the other farm of renewable energy technology. Although the choice of generator is not always desirable, the marine current generator required little variation in generator speed for optimise the output power and matching with the variation of marine current source. Hence squirrel cage induction generator (SCIG) is widely used as a generator in grid connected marine current power generator. In case of doubly fed induction generator (DFIG) based marine current generator power electronics frequency converters are used in rotor circuit. In case of permanent magnet generator (PMG) or in case of separately excited synchronous generator power electronics frequency converter is required in stator side for maintaining the frequency of generator when small variation has been occurred due to variation in marine current. The selection of generator from the various generator option is depends on the generator efficiency, reliability, cost, suitability and stability with grid connection.

2.4.3 Flicker

Flicker is a serious problem associated with the renewable energy power generation system. There are two types of flicker has been seen in the renewable energy conversion devices, frequency flicker and voltage flicker. When the marine current power generator is driven by the flowing water of oceans due to the pulsating nature of water flow the speed of the rotor is also varying. The frequency of the system is depends on the speed of the rotor so the frequency [34-35] is pulsating at PCC or frequency flicker has been occurred in the system. The terminal voltage of marine current generator is varying because of the pulsating nature of source so that voltage flicker may be seen at PCC. To reduce the voltage flicker shunt filter or capacitor has been used. It maintain the voltage at PCC constant, shunt capacitor reduce the voltage flicker in significant amount. To reduce the frequency variation or frequency flicker power electronics frequency conversion devices has been used at the terminal of the generator or at PCC.

2.4.4 Voltage Distortion

The total harmonic voltage distortion (THVD) limit at PCC has been given in the table 3. These limits are important when power electronics controller has been used in the marine current generator because power electronics converters are non-linear device they inject the harmonic currents in the grid. The magnitude of the harmonic currents should be limited to avoid exceeding THVD [36] permissible limit basically in high impedance network. Generally power electronics converter consist a filter to reduce the harmonics current injected in the network to a permissible level. If the grid connection is week or impedance of the network is high, the THVD can be exceeding the permissible limit so further filtration is required to reducing the harmonics current up to permissible limit.

Table 2.3: Voltage Distortion Limits

Voltage Level	Total Harmonic Voltage Distortion (%)
LV 2.5	2.5
MV	2.0
38 kv	1.5

2.4.5 Maximum Voltage Levels

The pulsating nature of marine energy and high ratio of peak to average power can vary the magnitude of voltage in significant amount at the PCC. The maximum permissible voltage level is given in table 2.4 if the variation in voltage magnitude at PCC exceeds the permissible limit it can damage the insulation of equipment connected at PCC. So it is very essential to maintain the maximum voltage within the permissible limit. For limiting the maximum voltage some variable speed control strategy has been adopt to the rotor or power electronics converter with storage device to be connected at PCC.

Table 2.4 Maximum allowed voltage levels at PCC

Nominal or rated Voltage	Maximum allowed Voltage
230 V	253 V
400 V	440 V
10 Kv	11.3 Kv
20 Kv	22.5 Kv
38 Kv	43.8 Kv
110 Kv	120 Kv

2.4.6 Reactive Power Requirements

In marine current power generation system generally induction machine has been used as a generator due to the pulsating nature of marine current or rotor speed. The induction machine required reactive power [37] for its operation it can be provided by two ways first one is locally generate through synchronous condenser or shunt capacitor connected at generator terminal. The second one is it can supply from the grid in case of grid connected marine current power generation system. An important analysis has been done in this work is if marine energy is connected to grid through HVDC Link then grid should be unable to supply reactive power because of no reactive power flow through the HVDC Link so it should be provided by locally generated reactive power. Induction machine always required reactive power it is used as a motor or as a generator if it is used as a generator cost should be increased because of the arrangement of reactive power support but in case of renewable energy generator induction machine is desirable due to variable speed up to some instant.

2.4.7 Grid-side Challenge

There are several challenges facing by marine energy developer when they try to connect the marine energy into the grid. It associated with the cast, onshore grid infrastructure, stability of the system. The research has been carried out to meet these challenges or removing the obstacles in grid connection [38-40] of marine current farm. The major problem facing by marine energy developers while in grid connection is flicker in voltage and frequency of marine current power. For reducing these problems power electronics converter or HVDC Link has been used. The power electronic converters produce the harmonic currents in the system for eliminating the harmonic current filter has been used.

CHAPTER 3

HVDC LINK

3.1 Introduction

The HVDC Link has been used in this work for connecting the marine current generator to the grid. It provides the asynchronous link between the marine current generator and the grid. Marine current generators generate the frequency flicker because of the variation in the marine current resource. The HVDC Link has been eliminate this problem by converting the variable frequency AC power into DC power by VSC at generator side and supply DC power to the VSI at grid side, the VSI invert in DC into the desirable AC current and supply to the Grid. HVDC Link contains power electronics converter at both end it generate the harmonics current to eliminate the harmonic current produced by converter filters are used at both end. The advantage of HVDC Link is absolute controllability of transmitted power through the firing angle control of thyristor. Modern converters are very fast and reliable.

The HVDC lines can be of two types: one with Conventional Line Commutated (LCC) technique [41] which uses thyristor for its working. The other one is based on Voltage Source Converter and Voltage Source Inverter (VSC-VSI) which uses PWM technique. In this work Line Commutated Converter (LCC) has been used for analysis as this type of HVDC line is conventionally is used for long time. A 12 pulse bridge converter has been considered for the LCC HVDC link.

3.2 Principle of DC Control

The power flow in a DC Link has been controlled by either voltage control or current control techniques [42]. For minimization loss in the system it is important to maintain terminal voltage constant in the link and adjust the current to give required the power. Current control strategy is also helpful for the voltage regulation and optimal utilization of the insulation. The advantage of DC line over AC line is the voltage drop is small due to the absence of reactive power drop. The study system is shown in fig 3.1 and steady state equivalent circuit has been shown in fig 3.2 with the assumption that the both poles of the converter is identical and have same delay angle. And also the number of bridge n_b connected in series at both end is same. The source voltages at both ends v_{dr} and v_{di} are defined as

$$v_{dr} = \frac{3\sqrt{2}}{\pi} n_b v_{vr} \cos \alpha_r \qquad 3.1$$

$$v_{di} = \frac{3\sqrt{2}}{\pi} n_b v_{vi} \cos\gamma_i \qquad 3.2$$

Where v_{dr} and v_{di} are line to line voltages of rectifier and inverter at valve side.

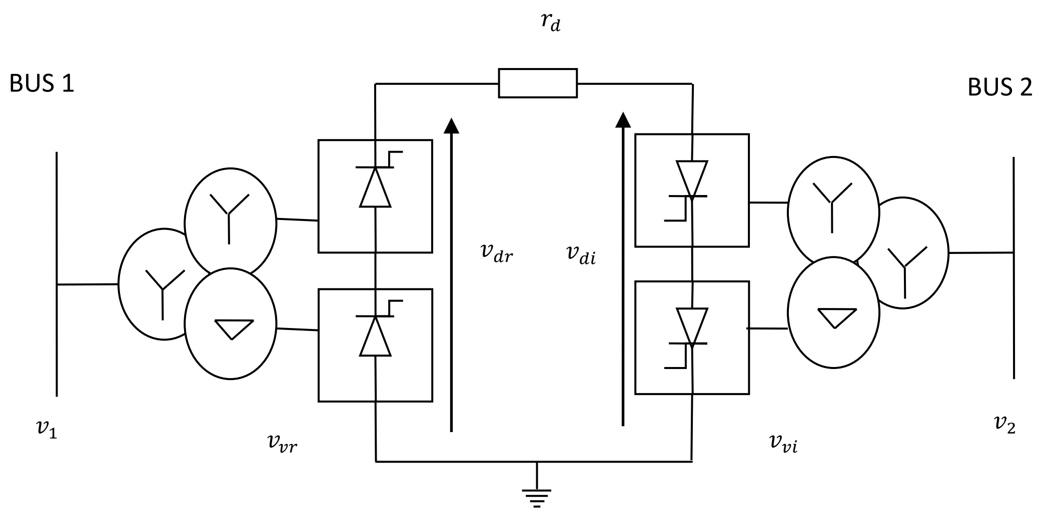


Fig. 3.1 Schematic representation of a two-terminal HVDC Line

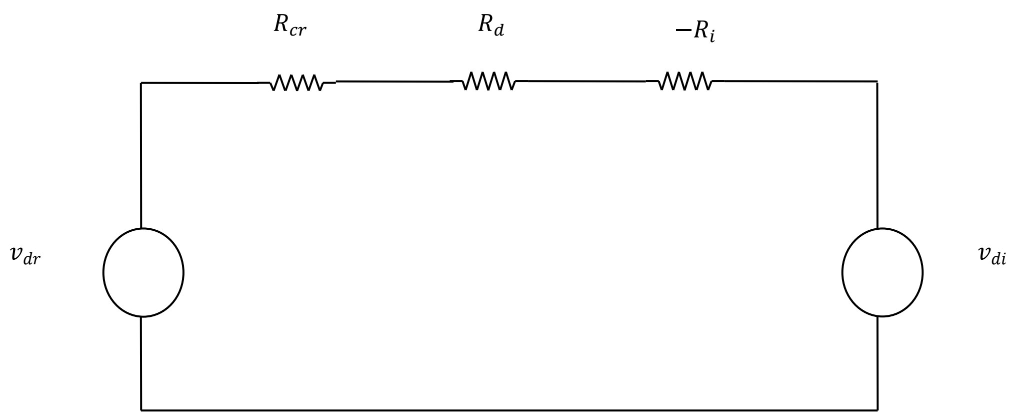


Fig. 3.2 Equivalent circuit of a two-terminal HVDC Line

From the fig 3.1 the voltage of valve side on both rectifier and inverter side can be calculated as

$$v_{vr} = \frac{n_{sr} v_1}{n_{pr} T_r} \qquad 3.3$$

$$v_{vi} = \frac{n_{si} v_2}{n_{pi} T_i} \qquad 3.4$$

Where $v_1$and v_2 are the AC line to line voltages at both generator and grid end respectively. T_r and T_i ate the nominal tap ratios of rectifier and inverter transformers.

v_{vi} Can also write as ….

$$v_{vi} = \left(\frac{A_i v_i}{T_i}\right)\cos\beta_i + 2vR_{ci}I_d \tag{3.5}$$

Where

$$R_{cr} = \frac{3n_b}{\pi}x_{cr} \tag{3.6}$$

$$R_{ci} = \frac{3n_b}{\pi}x_{ci} \tag{3.7}$$

Where n_b is the no of bridge, v_{dr} and v_{di} are the DC voltages of the rectifier and inverter side respectively,α_r is the firing angle of rectifierγ_i is the extinction angle of inverter, β_i angle of advance of inverter, x_{cr} and x_{ci} are the leakage reactance's of the rectifier and inverter side of converter transformer respectively and $r_d$is the DC resistance of the line.

The steady state current flow through the DC link

$$I_d = \frac{v_{dr} - v_{di}}{R_{cr} + R_d - R_{ci}} \tag{3.8}$$

$$I_d = \frac{\left(\frac{A_r v_r}{T_r}\right)\cos\alpha_r - \left(\frac{A_i v_i}{T_i}\right)\cos\gamma_i}{R_{cr} + R_d - R_{ci}} \tag{3.9}$$

From the above equation is has been consider that small change in v_r and v_i has large change in DC current if the control variables are to be constant. For fast and direct control of DC current is by varying the α_r and γ_i. To increase the power in the DC link by reducing the α_r which has been improve the power factor of rectifier and the inverter has been operate on minimum value of γ_i they should minimize the requirement of reactive power.

3.3 Current Control

The power flow through the HVDC Link has been control by mean of two ways either by voltage control or by the current control. Generally current control strategy has been adapt to maintained terminal voltage constant to minimize the losses in the system and improve the voltage profile of the dc link and reduce the voltage regulation. In this work current control scheme has been adapt for controlling the power at converter end and extinction angle control at inverter end. In this work the power flow through the DC link has been controlled by current control at the rectifier end and voltage control at the inverter end.

3.4 Smoothing Reactor

The smoothing reactor has been connected in series with the converter before the filters for smoothing the DC current ant reduce the ripple in DC current. It is reduce the harmonics in the current and voltage in DC link and reduce the fault current flowing through the converter during fault condition and protect the converter from the damage due to over-current. The size of the smoothing reactor depends on the lower order harmonics flow through the DC link and ripple in the DC links. To avoid the saturation of smoothing reactor during fault air core reactor has been used, it also prevent the converter station from the lighting strokes to the DC link.

3.5 Harmonics and Filter

The HVDC link contains the power electronics converter it inject the AC and DC harmonics in the system. The problem due to harmonics is listed below

- Extra power loss and heating of the machines
- Telephone and radio interference present in vicinity
- Noise in the system
- Over-voltage due to resonance
- Ripple in the DC current

A filter has been used to reduce or eliminate the effect of harmonics [43] in the system. AC filter has been used to eliminate the AC harmonics or harmonics present at ac side, band pass or high pass or low pass filter can be use according to the harmonics present in the system. Smoothing reactor has been used to reduce the DC harmonics or ripple in DC current.

The control of power in HVDC link is achieved through current control at rectifier end and voltage control at inverter end. Built in controller of DIgSILENT powerfactory software has been taken in consideration for this study. The converter's reactive compensation is provided by a combination of capacitor banks and ac filter

CHAPTER 4

MODELING AND SIMULATION OF MARINE CURRENT FARM CONNECTED TO GRID

4.1 Introduction

The design of marine current turbine is based on the diameter of the turbine, blade angle and rotational speed of the turbine. The basic dimension of marine current turbine has been shown in Fig 4.1, the diameter of marine current turbine has been 6 to 30 meter and it is installed in the seabed with the depth of 30 to 40 meter. The design of marine current turbine is similar to the wind turbine but the span of marine current turbine is small as compare to the wind turbine have 30 to 100 meter of diameter due to the density of water is high it has been around thousand times than the density of air. Thus the marine current turbine has been small diameter and lower speed. The marine current turbine required significantly low velocity of oceanic current to drive the MCT and generate the electricity as compare to the wind turbine witch required high speed wind to generate the same amount of power because of large density difference. The oceanic current speed 2.5 m/s is sufficient for the generation of electricity or for driving the marine current turbine. The energy density of water is higher than the energy density of air and more predictable. Low speed water flow impact the large force on the marine current turbine structure as compare to wind turbine due to the high density of water. The harnessing of kinetic energy of water through the marine current turbine is depends on the hydrodynamic characteristic of ocean water and the techniques witch has been adopt for the extraction of energy. The technique witch has been adopt for extraction of marine energy need to be describe the operational characteristic of the turbine and physical structure and location of the MCT. It does not consider only the design parameter and performance of the MCT but also the long term availability of the marine energy. Therefore, careful attention has been required for the analysis and simulation of the marine current energy generation and interconnection to the grid.

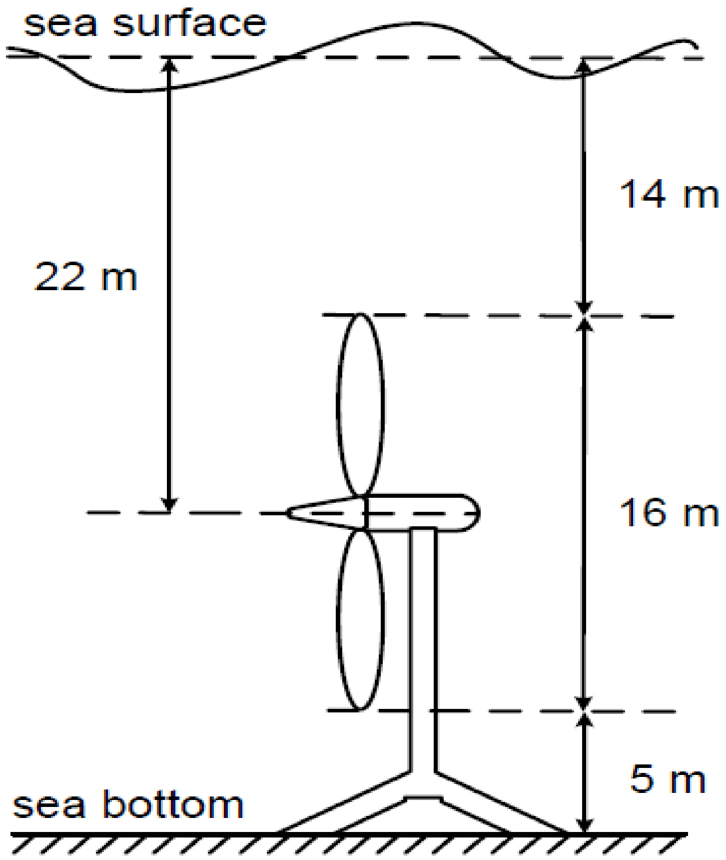


Fig 4.1 Basic dimension and location of MCT

In this simulation work two mass marine current turbines has been considered for the analysis of marine current farm connected to grid. It is assumed that both of the blades of turbine should be identical and combined torque has been considered. One mass is considered as the combined mass of generator rotor and gear box and another mass is considered as the combined mass of both the blade and hub of the turbine. Mutual damping is neglected for the simplification of the analysis. The system parameter has been considered as the combined torque of the turbine is T, the combined moment of inertia of rotor is j and stiffness constant is K.

4.2 Modelling of Marine Current Turbines

The block definition of a constant speed marine current turbine power generation system connected to Grid has been shown in Fig 4.2. For the variable speed of marine current the block definition has been shown in Fig 4.3.

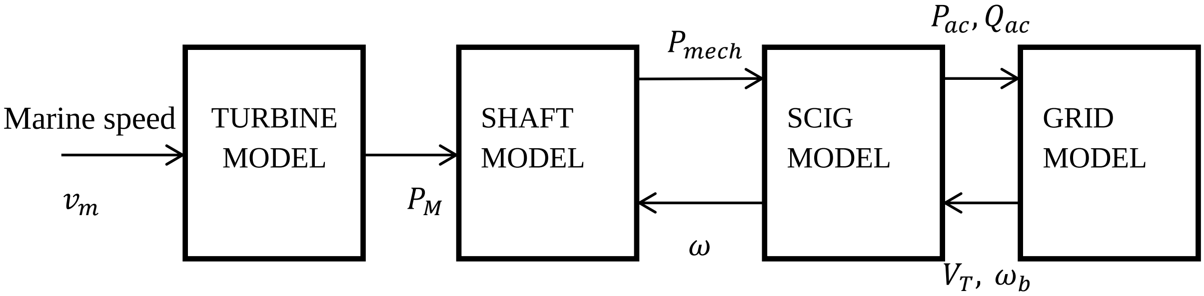


Fig 4.2 Block definition of marine current farm connected to Grid with constant speed

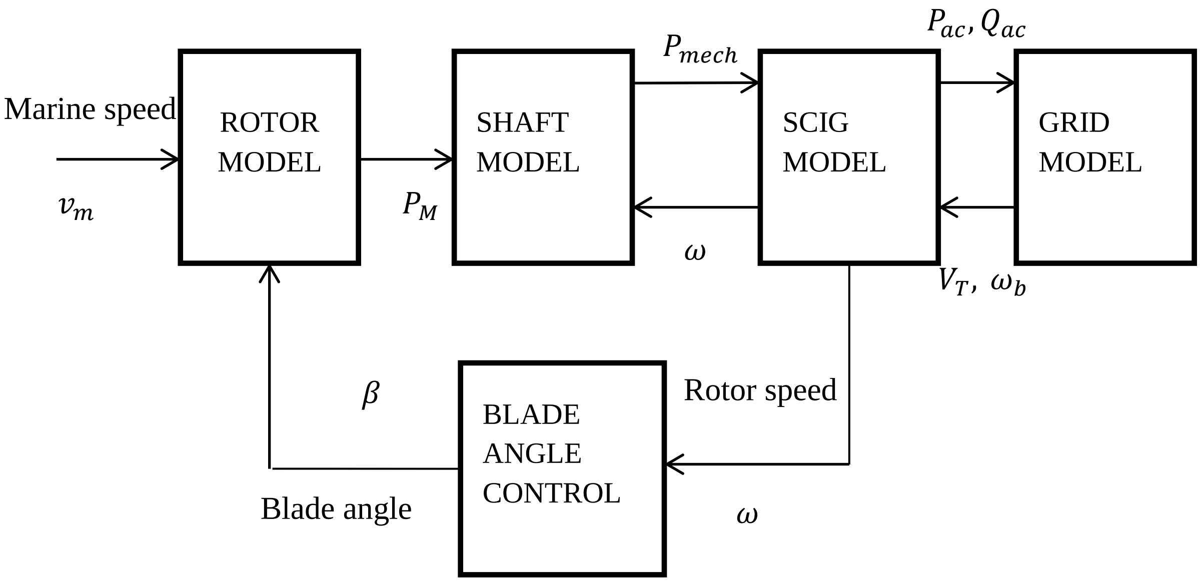


Fig 4.3 Block definition of marine current farm connected to Grid with variable speed and Blade angle control

4.2.1 Turbine modelling

The turbine modelling of marine current turbine in DIgSILENT power factory has been shown in Fig 4.3 it has been start with the block/frame definition is called turbine. This frame consist of

- Input signal: beta, omega_tur and Vm
- Output signal: Pmarine
- Block definition: marine power

The power generated by the marine current turbine is

$$P_m = \frac{1}{2}\rho_w.\pi R_{mct}^2 V_m^3 C_p(\lambda,\vartheta) \quad 4.1$$

Where R is the radius of the turbine, V is the speed of the marine current and Cp is the power coefficient of marine current turbine.

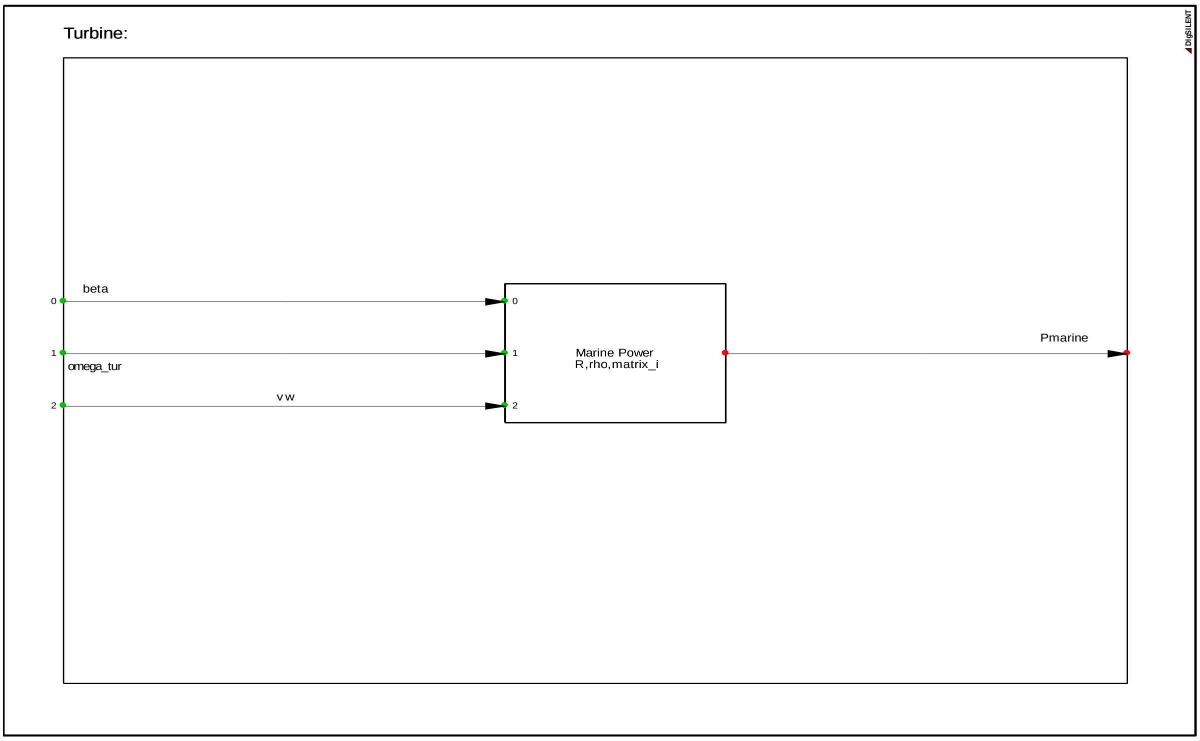


Fig 4.4 Simulation model of a marine current turbine on DIgSILENT power factory

Frame consist the variable definition and initial conditions of the equations which is put in the blocks. The variable definitions and initial condition which is put in the frame is given below

inc(Cp)=0.4

inc(vm)=pow((2*Pmarine*1E6/(rho*pi()*sqr(R)*0.4)),(1/3))

inc(lambda)=omega_tur*R/pow((2*Pmarine*1E6/(rho*pi()*sqr(R)*0.4)),(1/3))

vardef(R)='m';': Rotor Blade Radius'

vardef(rho)='kg/m3';': Air density'

The equation which is put in the block is given below

Pmarine=rho/2*pi()*sqr(R)*Cp*pow(vm,3)/1E6

Cp=sapprox2(beta,lambda,matrix_i)

lambda=omega_tur*R/vm

4.2.2 Shaft Modelling

The shaft modelling of marine current turbine in DIgSILENT power factory has been shown in Fig 4.4 it has been start with the block/frame definition is called shaft. This frame consist of

- Input signal: Pmarine, Speed_gen
- Output signal: Pt
- Block definitions: mass_1 Torque, Spring, Pt, Gear Box, Torque

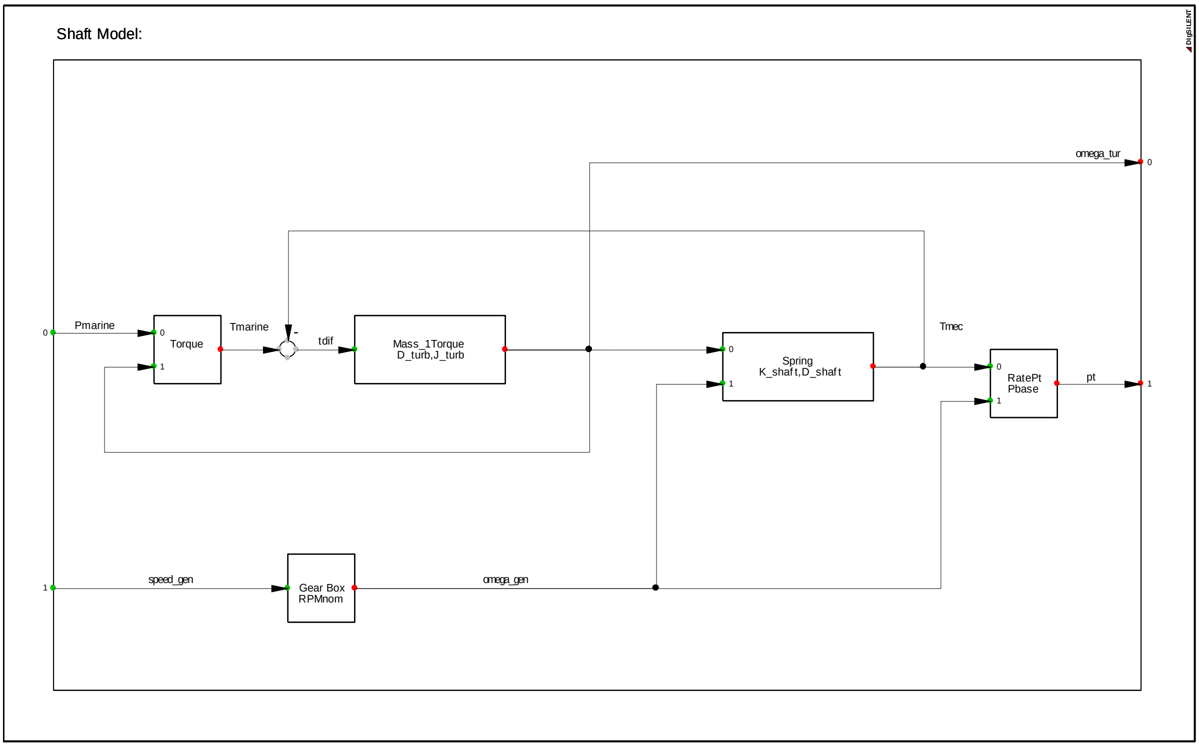


Fig 4.5 Shaft model of MCT on DIgSILENT power factory

Frame consist the variable definition and initial conditions of the equations which is put in the blocks. The variable definitions and initial condition which is put in the frame is given below

inc(Pmarine)=pt*Pbase

inc(omega_tur)=omega_gen

inc(Tmec)=pt/omega_gen*Pbase*1E6

inc(Tmarine)=Pmarine/omega_gen

inc(tdif)=0

vardef(RPMnom)='rpm';' Nominal Turbine-Speed';

vardef(J_turb)='kg mm';' Rotor Inertia (without generator)';

vardef(D_turb)='Nms/rad';' Turbine Damping';

vardef(Pbase)='MW';': Rated Power of Generator'

vardef(D_shaft)='Nms/rad';' Torsional Damping';

vardef(K_shaft)='Nm/rad';' Shaft Stiffness';

Block 1 Torque:

torque=Power/omega*1E6

Block 2: Mass_1 Torque:

![d]='p.u.'

![Ta]='s'

![RPMnom]='RPM'

![Pnom]='MW'

!inc(Ta)=J*sqr(RPMnom)/Pnom*sqr(2*pi()/60)/1000000

!inc(d)=D_turb*sqr(RPMnom)/Pnom*sqr(2*pi()/60)/1000000

speed_state.=(t1-D_turb*speed_state)/J

omega_tur=speed_state

inc(speed_state)=omega_tur

!omega_tur=speed_state

!inc(speed_state)=speed_tur

Block 3: Spring Torque

[omega1]='rad/sec.'

[omega2]='rad/sec'

[t1]='Nm'

!inc(k12)=K12*RPMnom/Pnom*(2*pi()/60/1000000)

!inc(d12)=D12*sqr(RPMnom)/Pnom*sqr(2*pi()/60)/1000000

inc(dphi12)=t1/K12

dphi12.=omega1-omega2

t1=K12*dphi12-D12*(omega2-omega1)

Block 4: Pt

[pt]='p.u.'

[omega_gen]='rad/sec'

[tg]='Nm'

pt=omega_gen*tg/1E6/Pbase

Block 5: Gear Box

omega=speed*RPMnom/60*2*pi()

4.2.3 Blade Angle Control

The blade angle control modelling of marine current turbine in DIgSILENT power factory has been shown in Fig 4.5 it has been start with the block/frame definition is called Blade Angle Control. This frame contains

- Input signals: speed
- Output signals: Beta
- Block definitions:

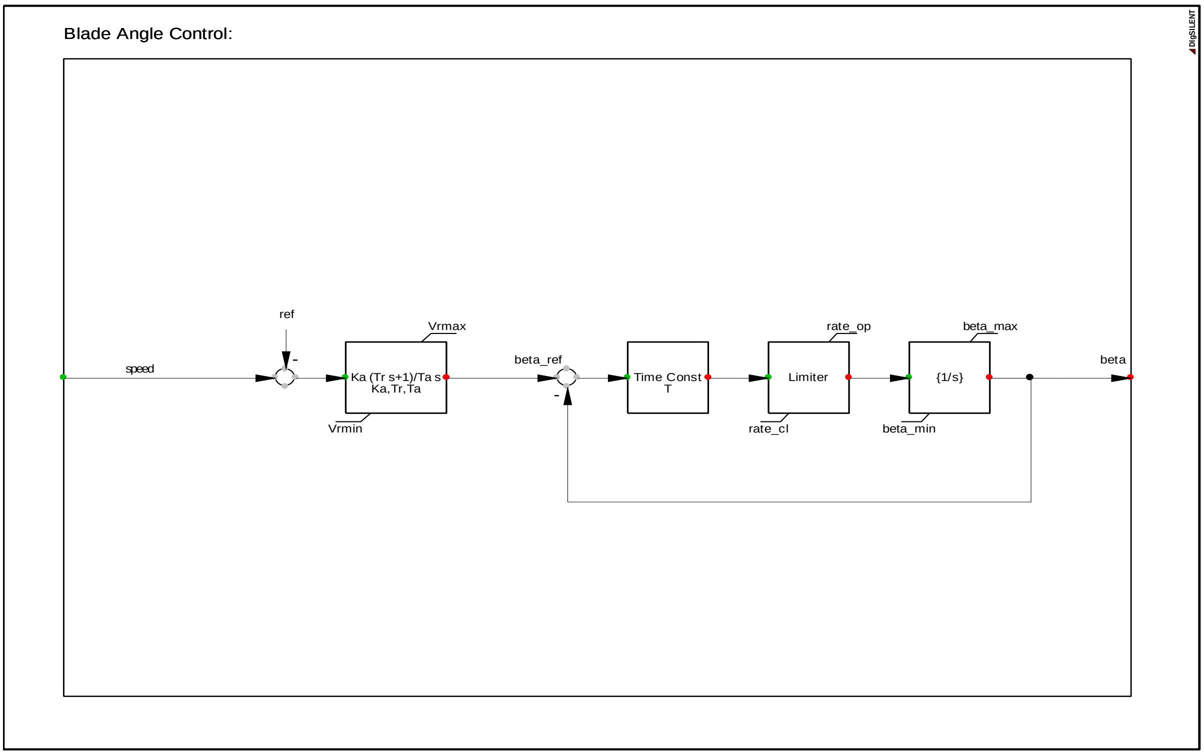


Fig 4.6 Blade angle control of MCT on DIgSILENT power factory

Frame consist the variable definition and initial conditions of the equations which is put in the blocks. The variable definitions and initial condition which is put in the frame is given below

inc(beta_ref)=Vrmin

inc(beta)=beta_min

inc(x1)=Vrmin

inc(x)=beta_min

vardef(Ka)   ='deg/p.u.';' Blade Angle Controller Gain'

vardef(Ta)   ='s';'Blade Angle Controller Time Constant'

vardef(Tr)   ='s';' Lead Time Constant'

vardef(T)   ='s';' Servo Time Constant'

vardef(rate_op)   ='deg/s';' Opening Rate of Change Limit'

vardef(rate_cl)   ='deg/s';' Closing Rate of Change Limit'

vardef(beta_max)   ='deg';' Max. Blade Angle'

vardef(beta_min)   ='deg';' Min. Blade Angle'

vardef(ref_speed)   ='p.u.';' Speed Reference'

Block 1: Ka(Trs+1)/Tas

dx=Ka*yi/Ta

! x.=select({dx>0.and.x>=Vrmax}.or.{dx<0.and.x<=Vrmin},0.0,dx)

x.= dx

y1=limstate(x, Vrmin, Vrmax)

yo=lim(y1+Tr*dx, Vrmin, Vrmax)

limits(Ta) = (0,)

Block 2: Time Constant

yo=yi/K

Block 3: Limiter

yo=lim(yi,y_min,y_max)

Block 4: (1/S)

x.=yi

yo=limstate(x, Ymin, Ymax)

4.2.4 Frame

In order to define the interaction blocks and signals flows a frame called marine turbine frame.

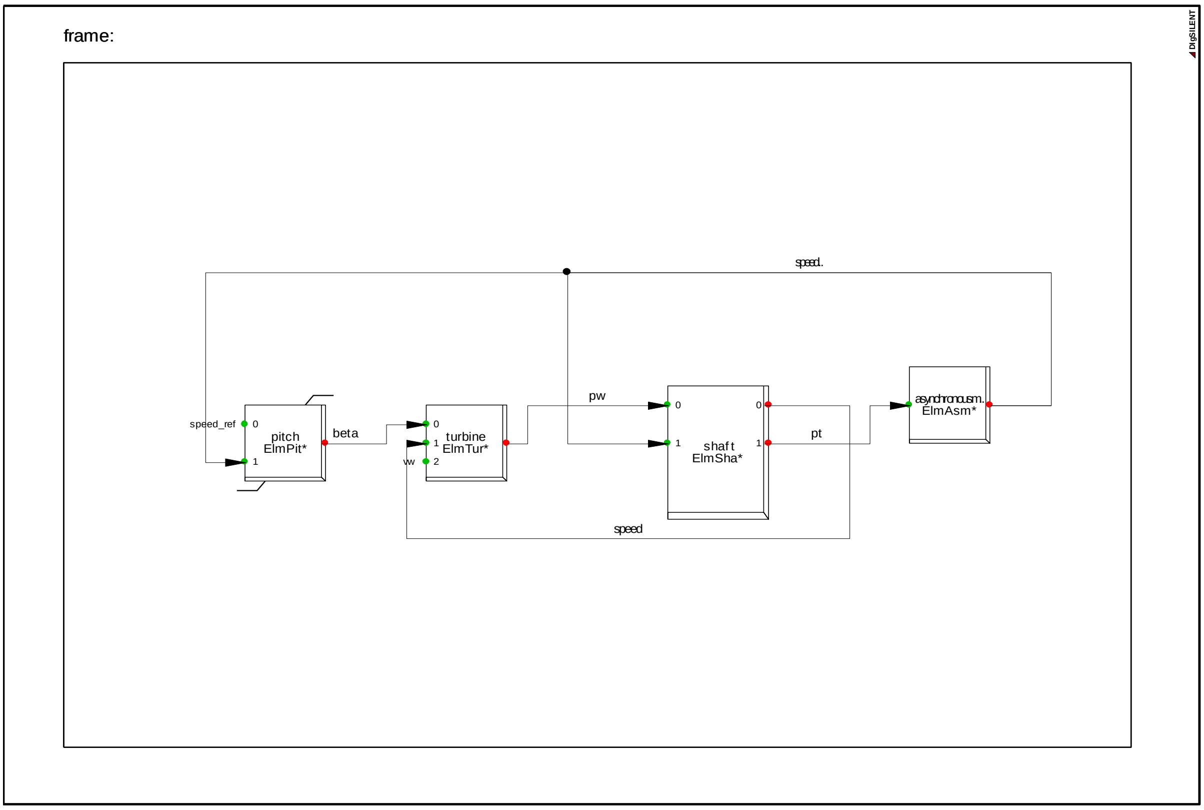


Fig 4.7 Frame of the MCT

4.3 Induction Generator modeling

The Powerfactory model uses rotor flux and stator currents as a state variable, for the stability analysis of induction machine it has been represented with following equations.

$$v = r_s i_s + \frac{d\varphi_s}{\omega_n dt} + j\frac{\omega_{ref}\varphi_s}{\omega_n} \qquad 4.2$$

$$0 = r_r i_r + \frac{d\varphi_r}{\omega_n dt} + j\frac{\omega_{ref} - \omega_r}{\omega_n}\varphi_r \qquad 4.3$$

where v is the stator voltage in volts, r_s is the stator resistance in ohms, i_s is the stator current in A, φ_s is stator flux, ω_n is nominal frequency, ω_{ref} is the system frequency, r_r is rotor resistance in ohms, i_r is rotor current in A, and φ_r is rotor flux.

4.4 SIMULATION ON STABILITY STUDY IN DIGSILENT POWERFACTORY

4.4.1 Configuration of the Studied Marine Current Power Generation System

The study system considered here is a 200 MW Marine Current Farm (MCF) with a number of marine current turbines coupled with SCIG through the gear box has been connected to the Point of Common Coupling (PCC) through connecting lines and step-up transformer. The gear box (GB) has been used to convert the low rotational speed of MCT into the high rotational seed as for the requirement of the induction generator (IG). The power generated by MCT is exported to grid through an AC Transmission line in parallel with a HVDC link as shown in Fig. 4.7. To simplify the analysis aggregated model of MCT has been used, based on simple assumption that all MCT are operating coherently and mutual damping has been neglected. The aggregated model of marine current farm connected to grid has been shown in Fig. 4.8. The transformer and connecting lines are represented as a series resistance and impedance $r_L + jx_L$ in the circuit and the conventional AC transmission line also represented as a series resistance and impedance $r_T + jx_T$ in the circuit. The HVDC Link has been used to convert the variable generated voltage into the constant voltage because of the variable voltage generated by the marine current generator. The renewable energy generators facing problems of the voltage and frequency flicker due to the variation in the marine current. The HVDC link convert the variable AC into constant DC at generator end and send to the inverter which is connected to the Grid, Inverter convert the constant DC into the desirable AC and export to the Grid. In case of only HVDC link connected to grid local generated reactive power is required to the IG for build-up the voltage so capacitor bank or synchronous condenser is connected to the PCC.

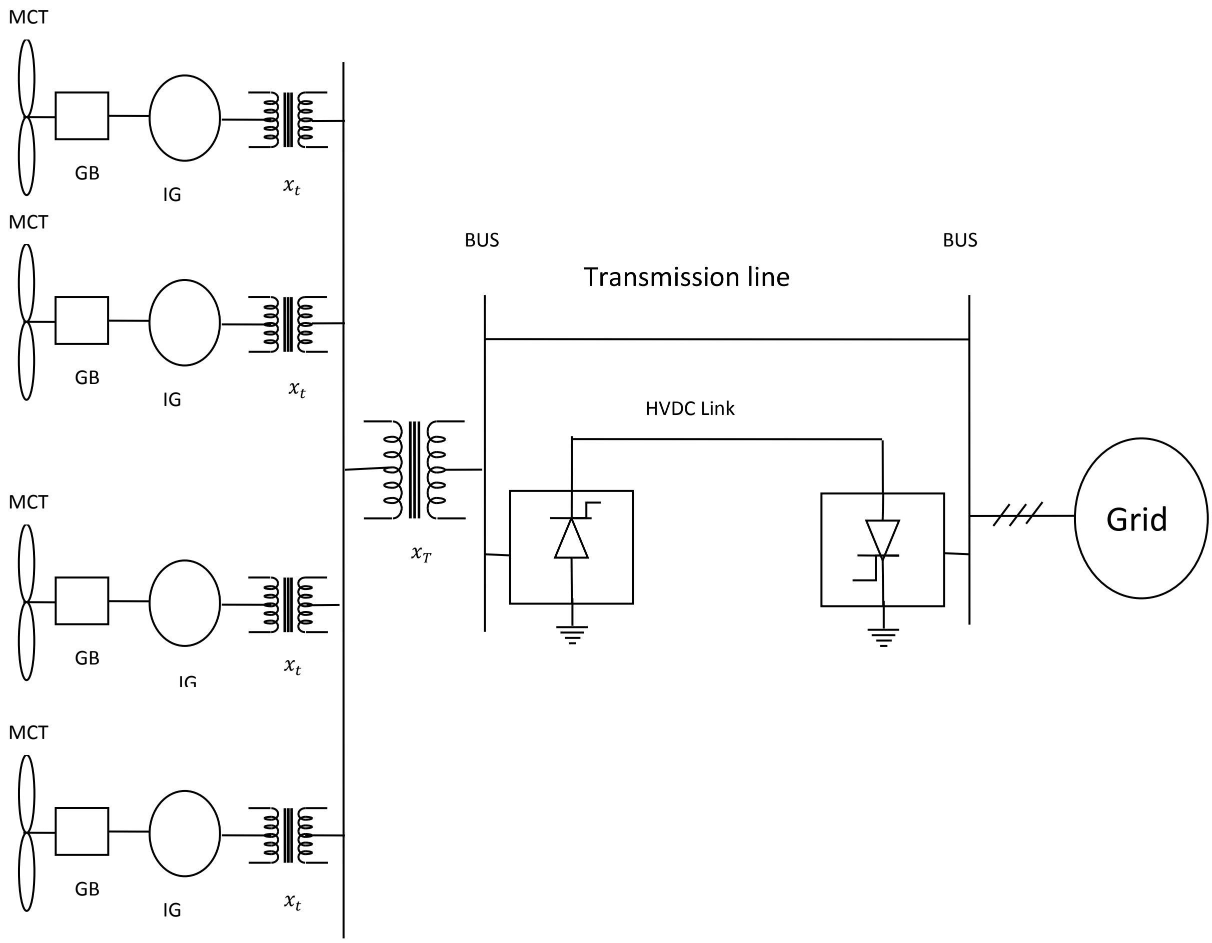


Fig 4.8 Circuit topology of marine current form connected to grid with AC transmission lines and HVDC Link

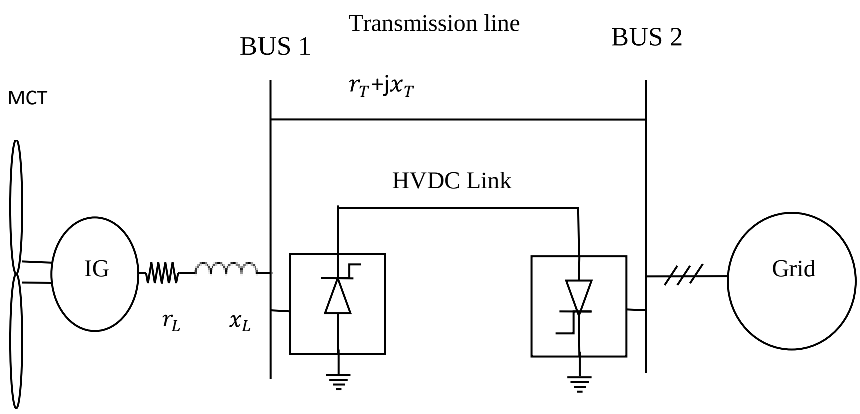


Fig. 4.9 Schematic representation of a marine current form connected to grid with AC transmission line and HVDC Link

4.4.2 Simulation model of marine current farm connected to grid on DIgSILENT power factory

The entire modelling and simulation of studied system marine current farm connected to grid has been performed on the DIgSILENT power factory software. The simulation model of the studied system has been shown in Fig 4.9. In this simulation to extract the power from the kinetic energy of the marine current, marine current turbine has been coupled with induction generator has been connected to the generator bus and synchronous condenser is connected to the generator bus for supporting and supplying the reactive power requirement of the induction generator and the system. The generator bus connected to the PCC through the step-up transformer and the PCC is connected to the Bus 1 through the step-up transformer the boost the generated voltage to the high transmission voltage level and connected to the Grid.

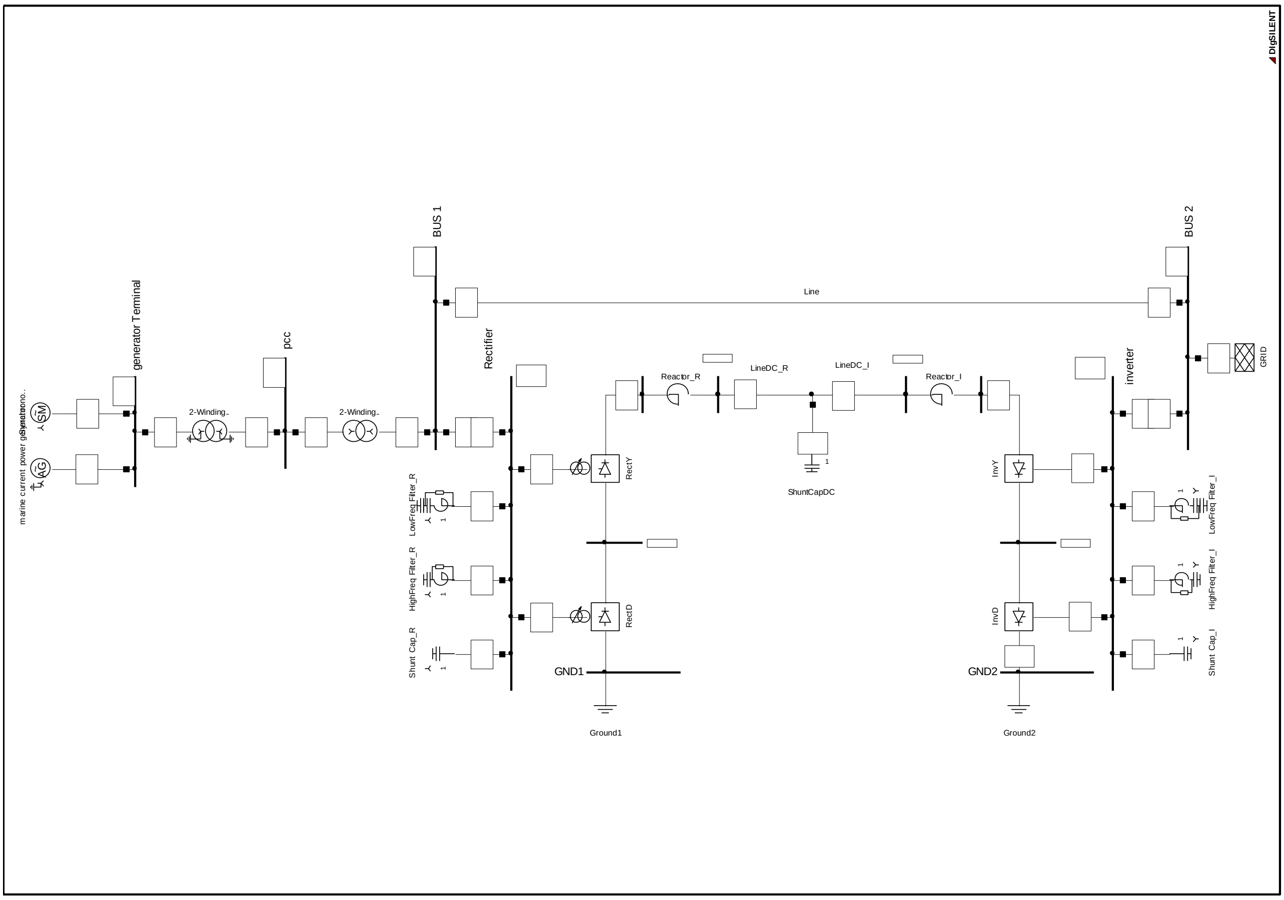


Fig. 4.10 Simulation diagram of marine current farm connected to grid

CHAPTER 5

RESULTS AND DISCUSSION

The stability study analysis has been performed in RMS simulation of DIgSILENT powerfactory software. The stability of study system has been analysed with terminal voltage, rotor angle, active and reactive power for fault duration of 0.01 sec at generator terminal at t=1sec.

An important observation that can be done in this analysis is that since IG required reactive power either the reactive power should be made available to IG through grid or has to be generated locally. In case of HVDC line no reactive power can be transmitted through line with LCC there for a local reactive generator has been connected at the point of LCC which is in the form of synchronous condenser at PCC. The turbines are assumed to be operating at its rated power and speed during simulation.

The entire study has been performed with MCF in following configurations below

1. With only AC Transmission line.
2. With only HVDC line.
3. With both AC and HVDC line together carrying 50% of the total loads each.

Case 1:

When the marine current Farm connected to the Grid with only AC line, performance analysis with turbine power, terminal voltage, rotor angle, active and reactive power shown in Fig 5.1 (a) to 5.1 (f).

Case 2:

When the marine current Farm connected to the Grid with only ac line, performance analysis with turbine power terminal voltage, rotor angle, active and reactive power shown in Fig 5.2 (a) to 5.2 (f).

Case 3:

When the marine current Farm connected to the Grid with only ac line, performance analysis with turbine power terminal voltage, rotor angle, active and reactive power shown in Fig 5.3 (a) to 5.3 (f).

Performance analysis of the marine current farm when connected only through the AC line to the grid.

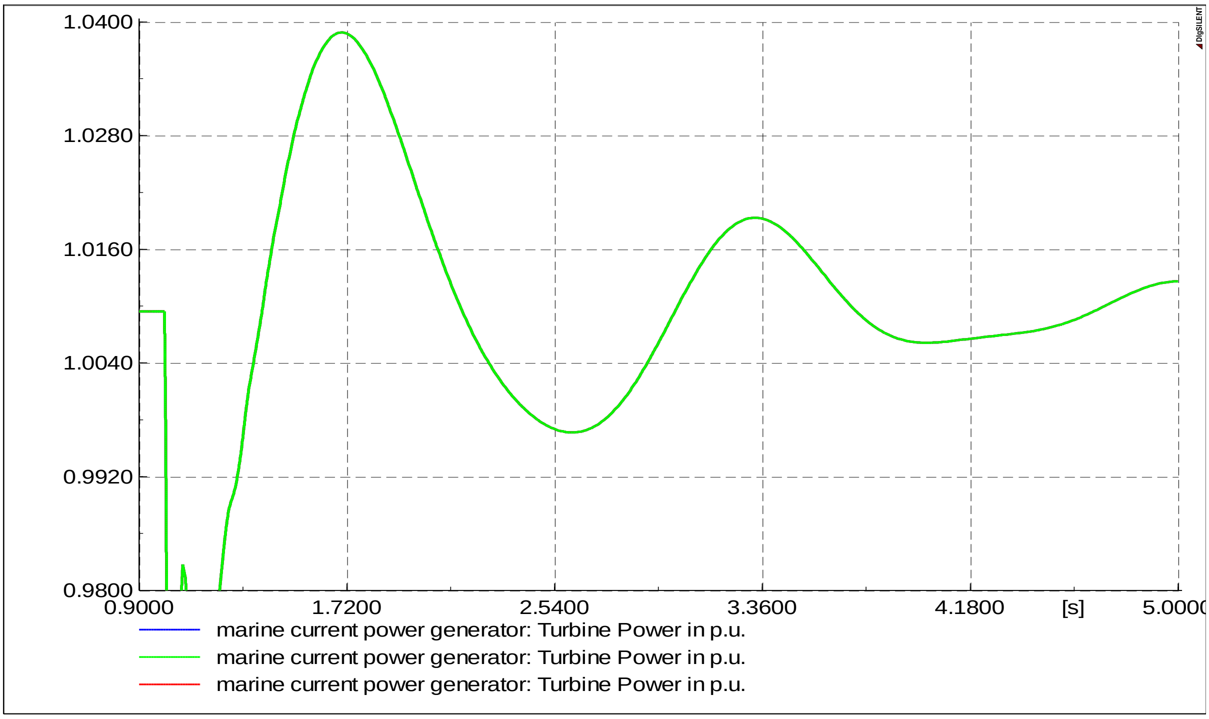


Fig 5.1 (a) Turbine power of MCT connected to Grid with only AC Transmission line

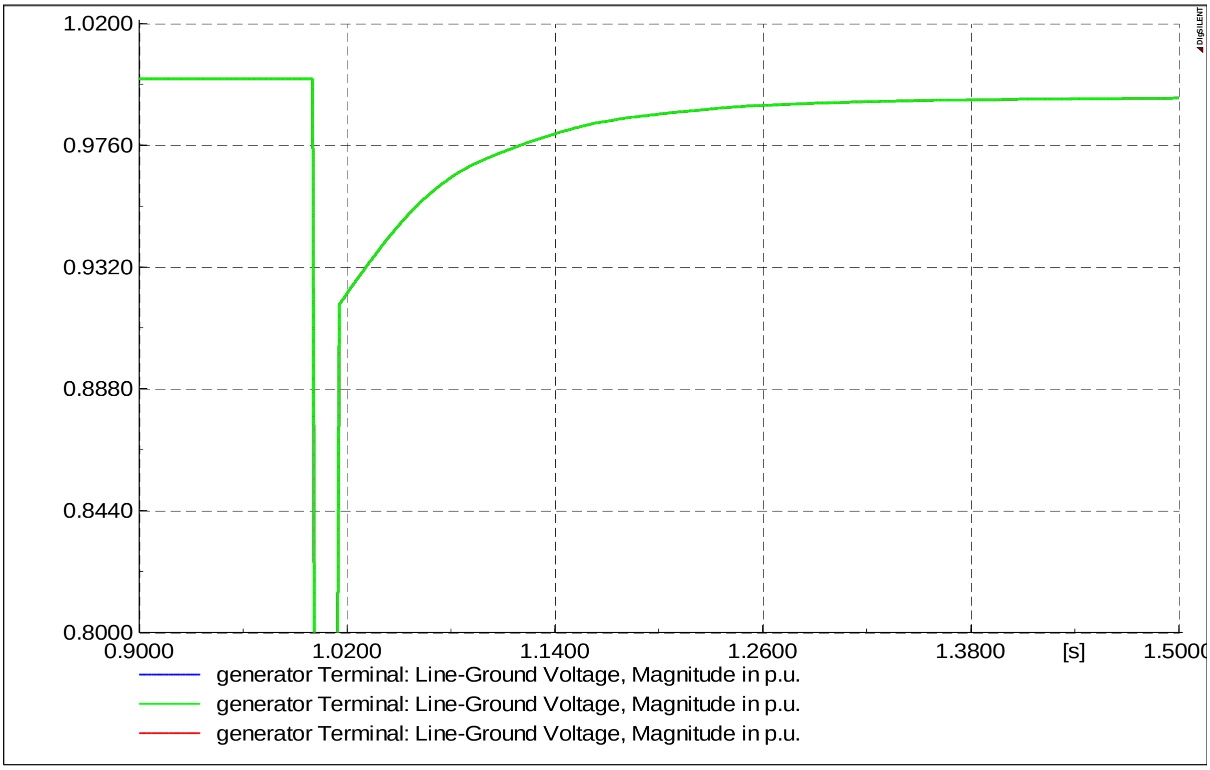


Fig 5.1 (b) Generator terminal voltage of MCT connected to Grid with only AC Transmission line

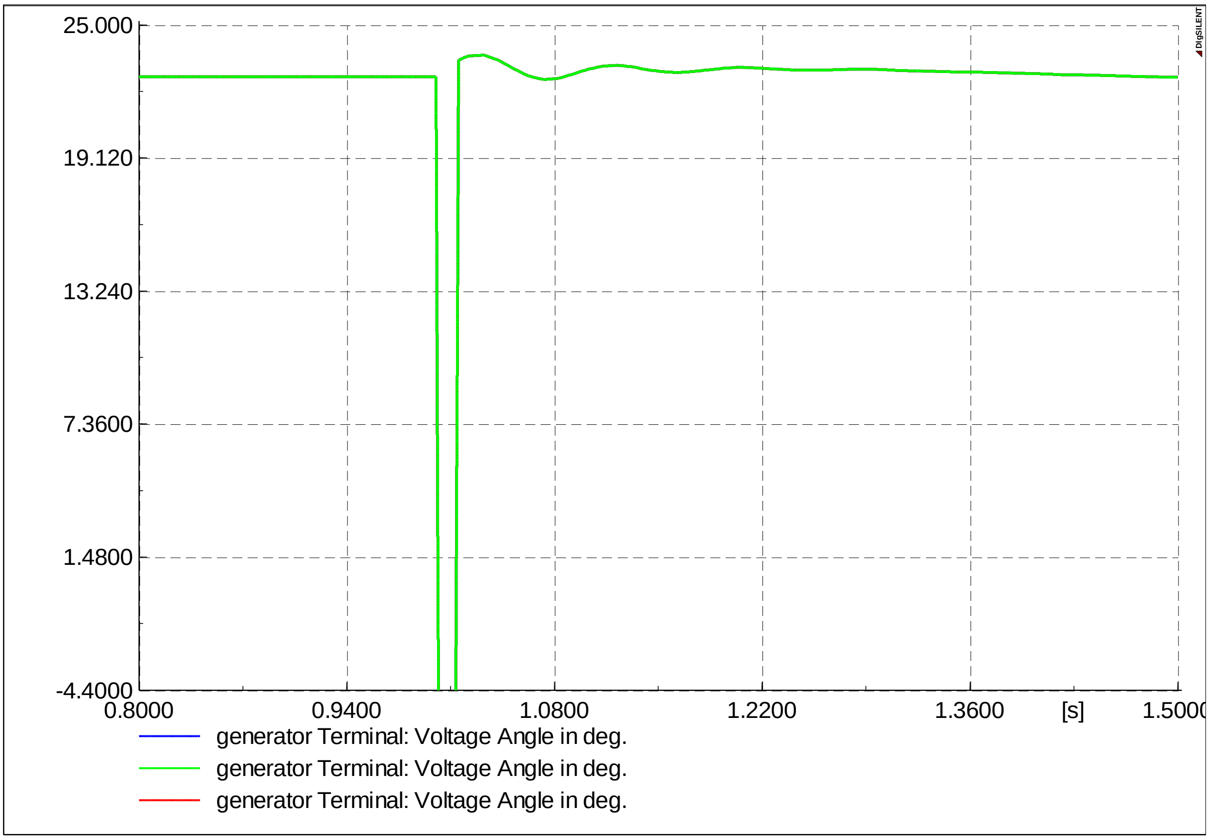


Fig 5.1 (c) Voltage-angle of MCT connected to Grid with only AC Transmission line

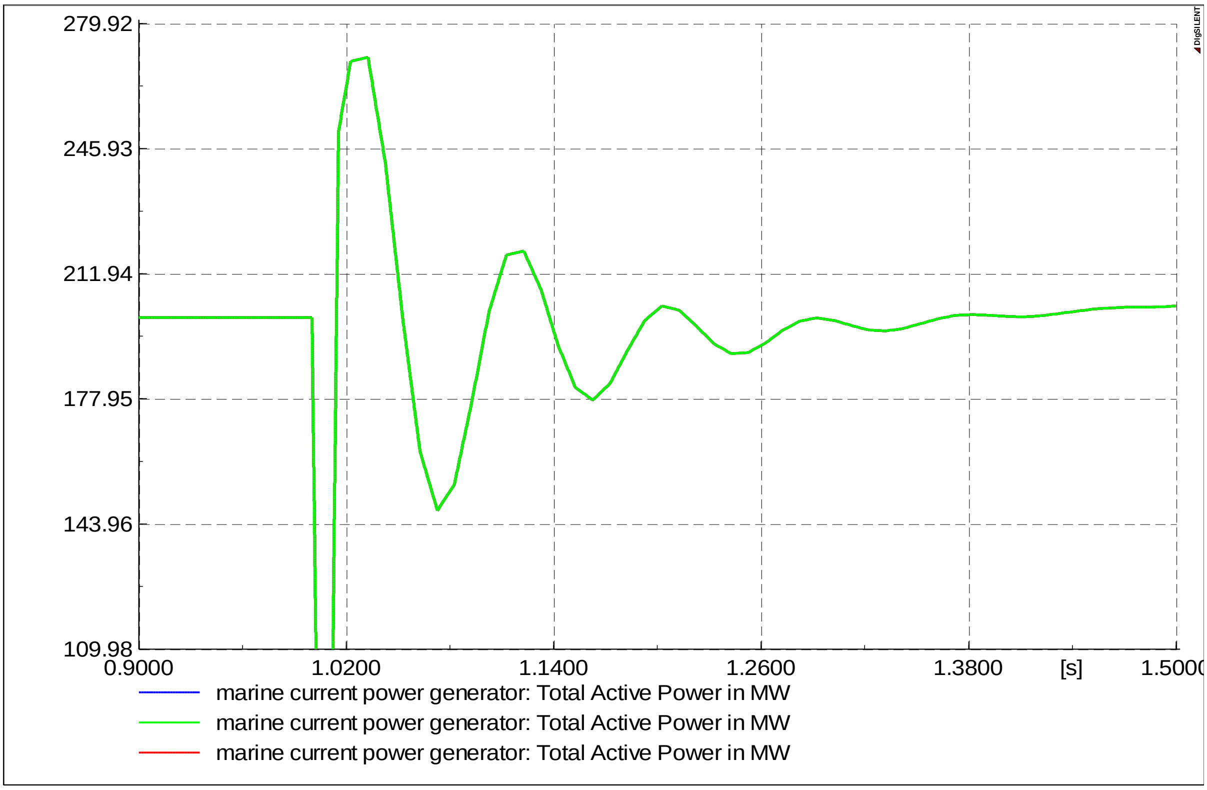


Fig 5.1 (d) Total active power of marine current generator connected to Grid with only AC Transmission line

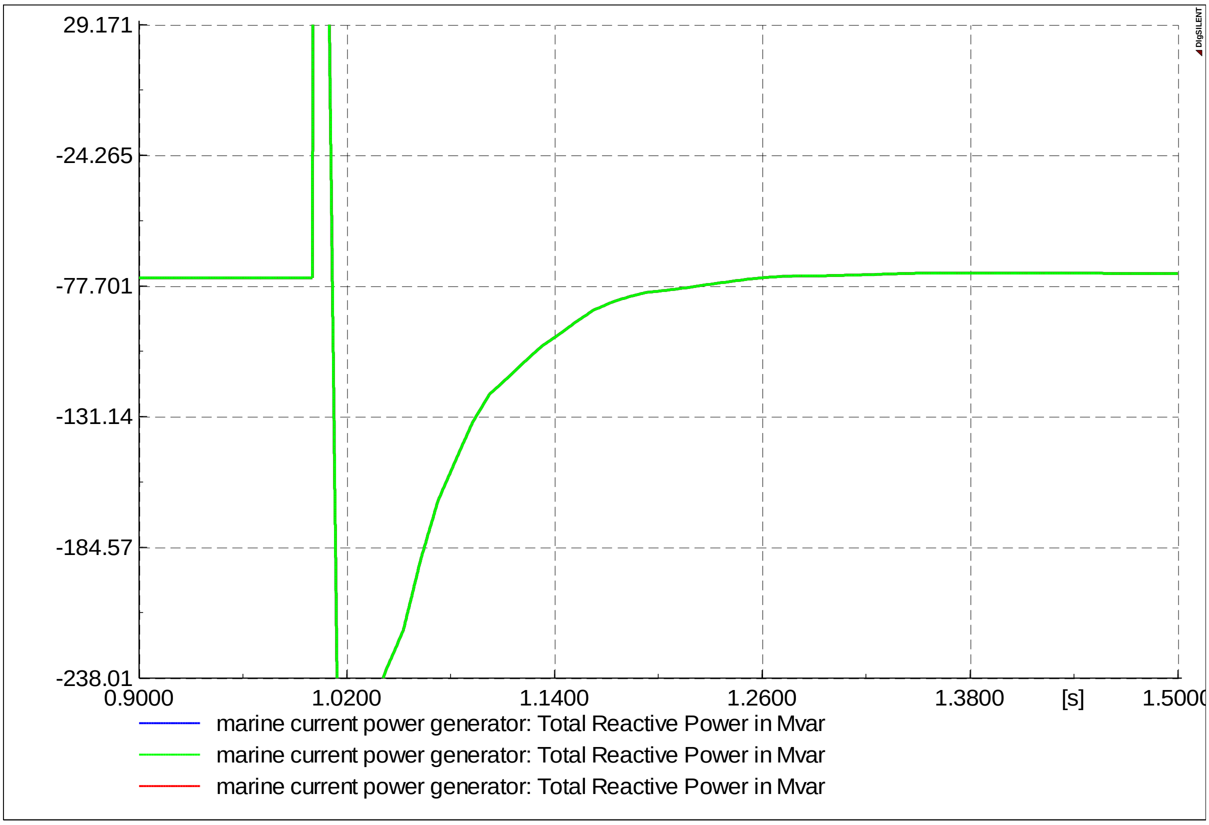


Fig 5.1 (e) Total reactive power of marine current generator connected to Grid with only AC Transmission line

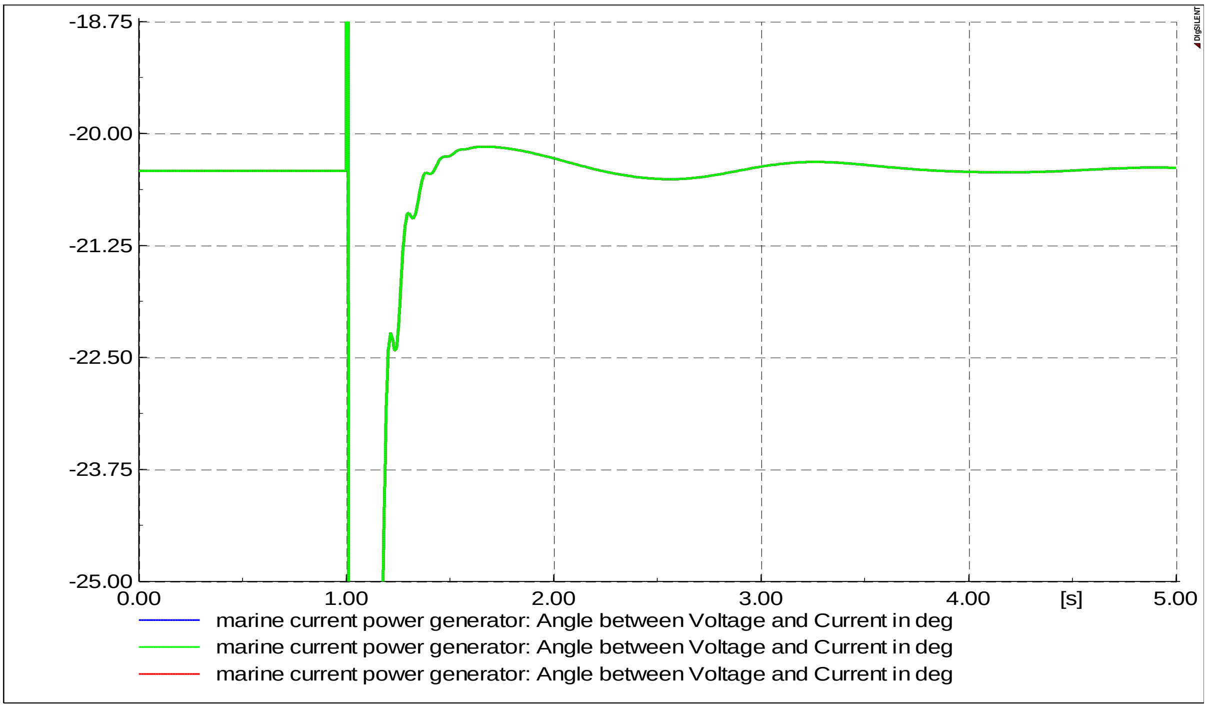


Fig 5.1 (f) Angle b/w voltage and current of marine current generator connected to Grid with only AC Transmission line

Performance analysis of the marine current farm when connected only through the HVDC line to the grid

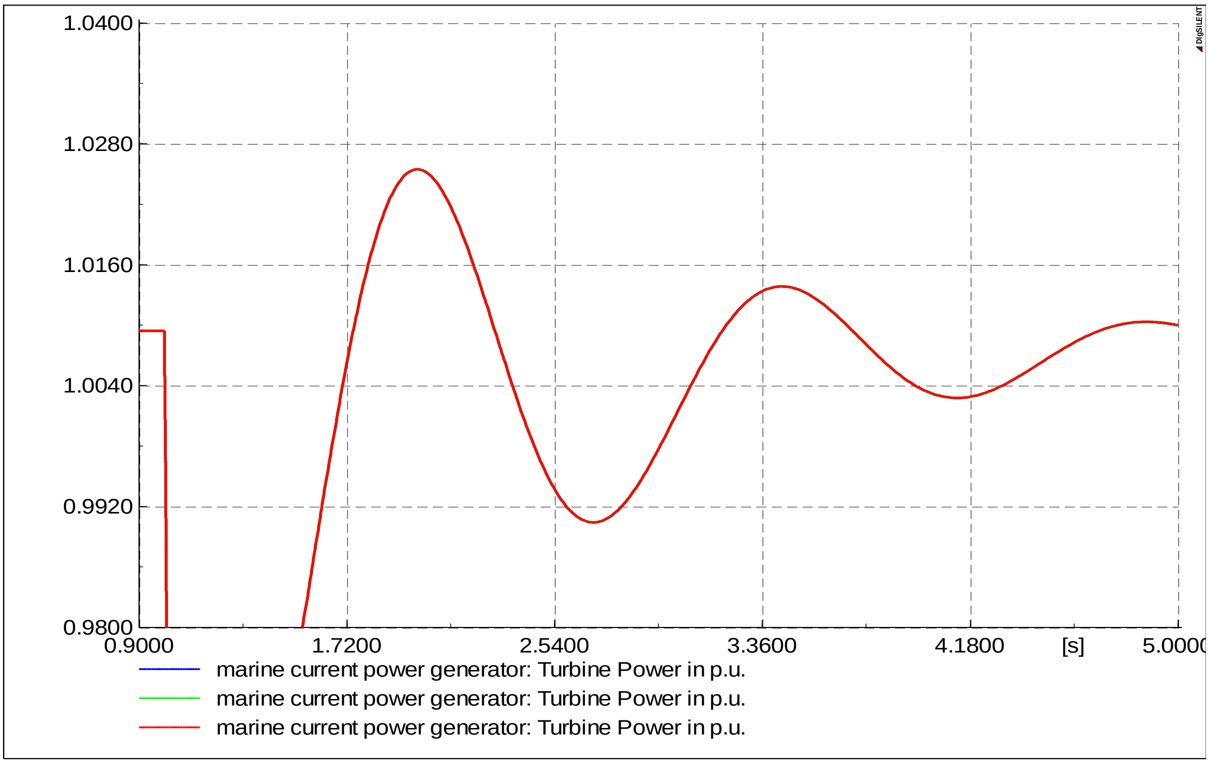


Fig 5.2 (a) Turbine power of MCT connected to Grid with only HVDC Transmission line

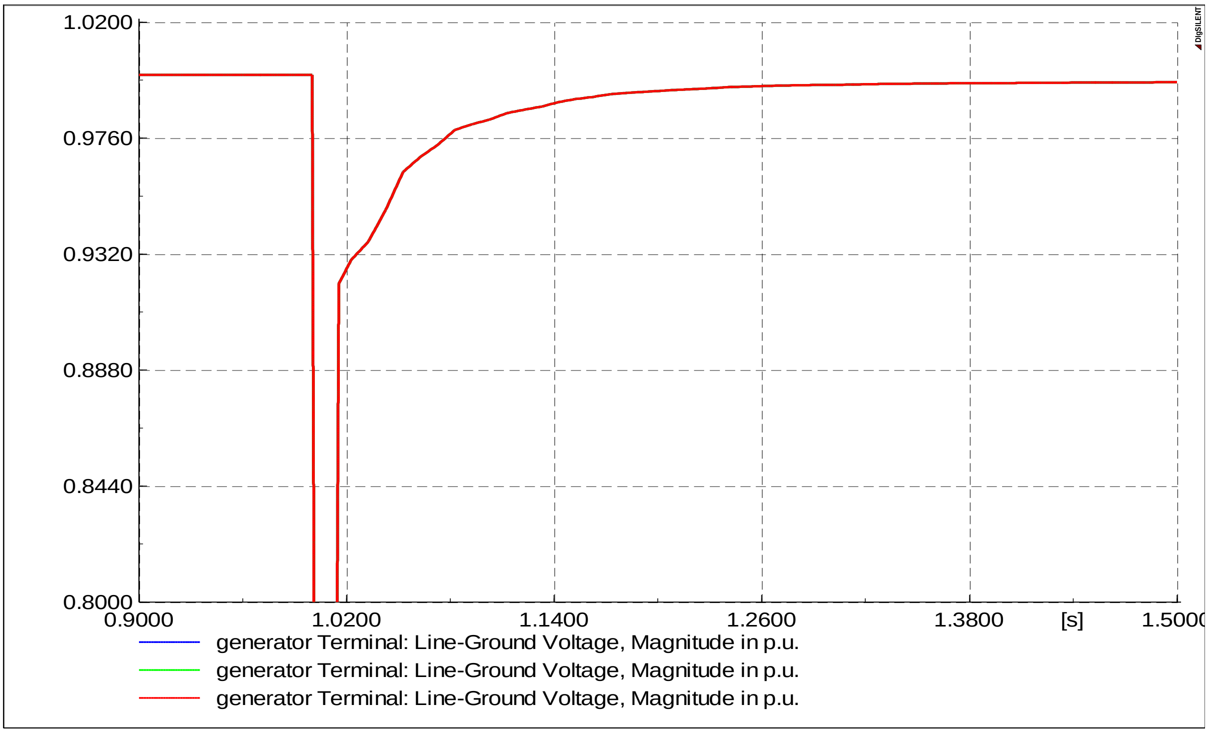


Fig 5.2 (b) Generator terminal voltage of MCT connected to Grid with only HVDC Transmission line

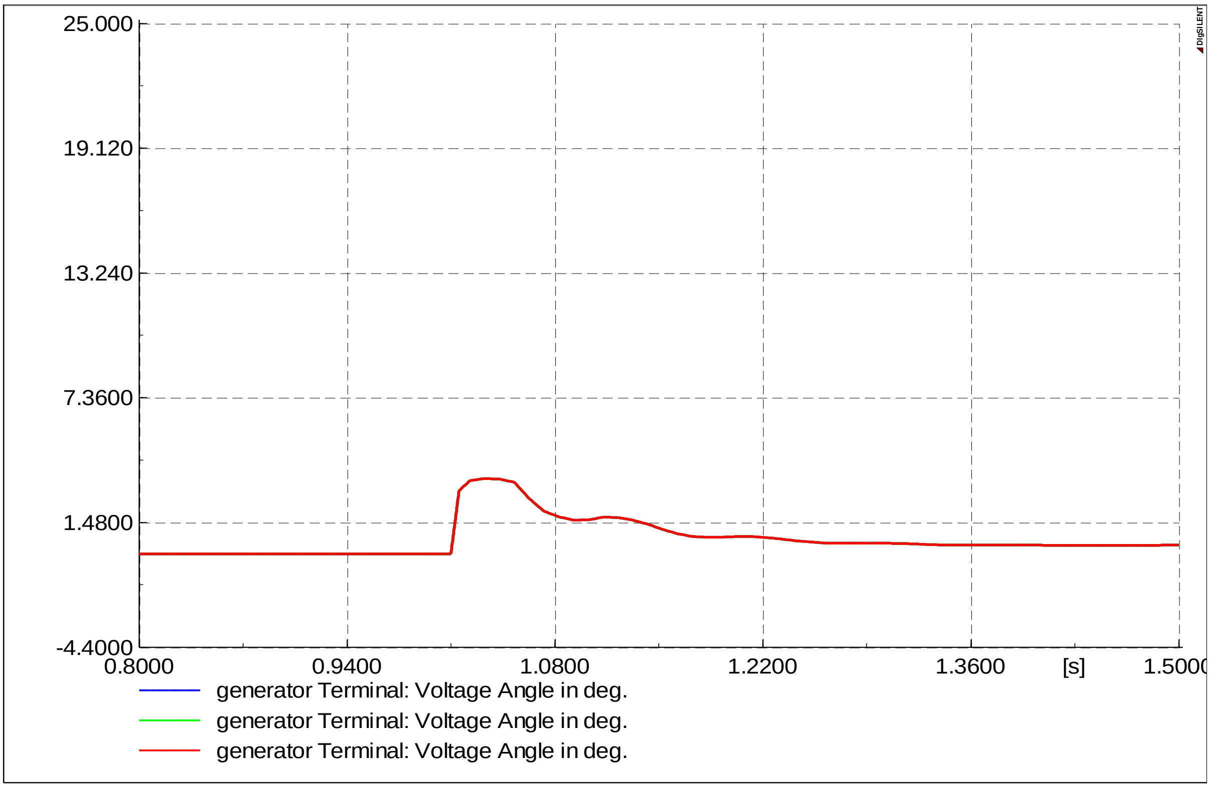


Fig 5.2 (c) Voltage-angle curve of MCT connected to Grid with only HVDC Transmission line

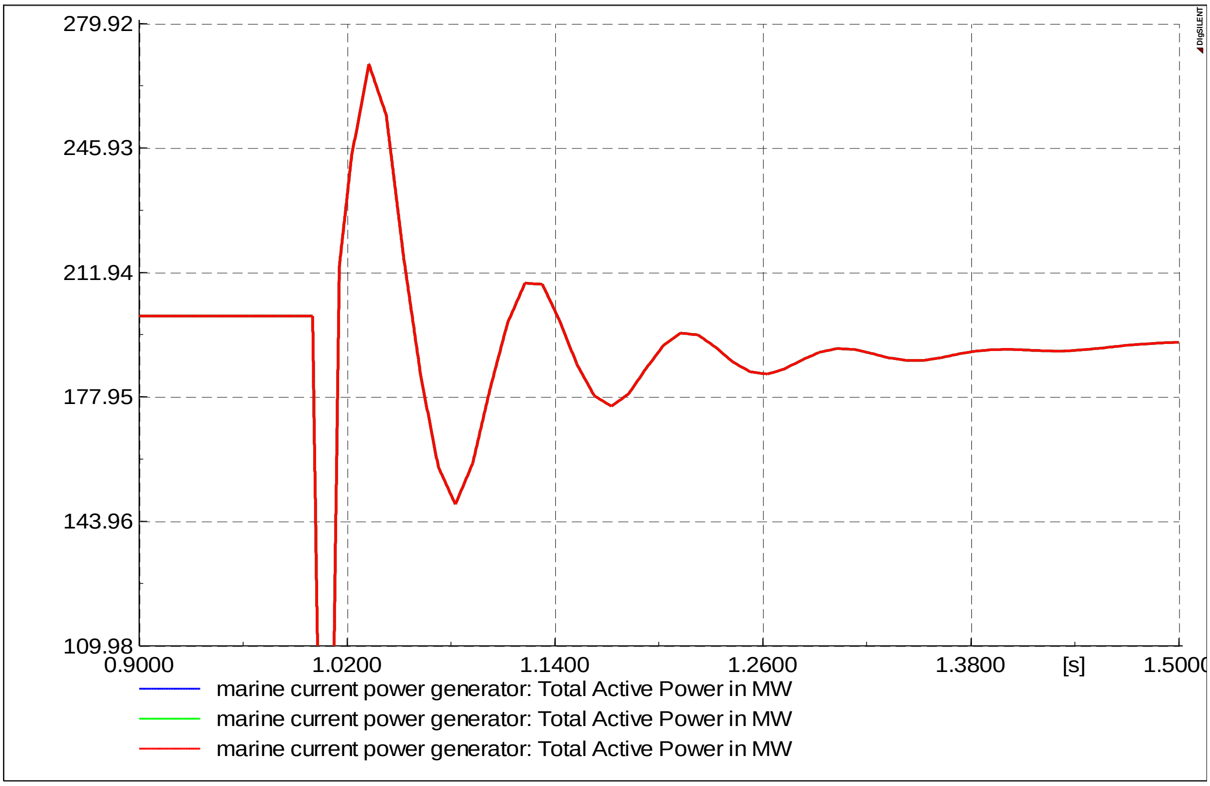


Fig 5.2 (d) Total active power of marine current generator connected to Grid with only HVDC Transmission line

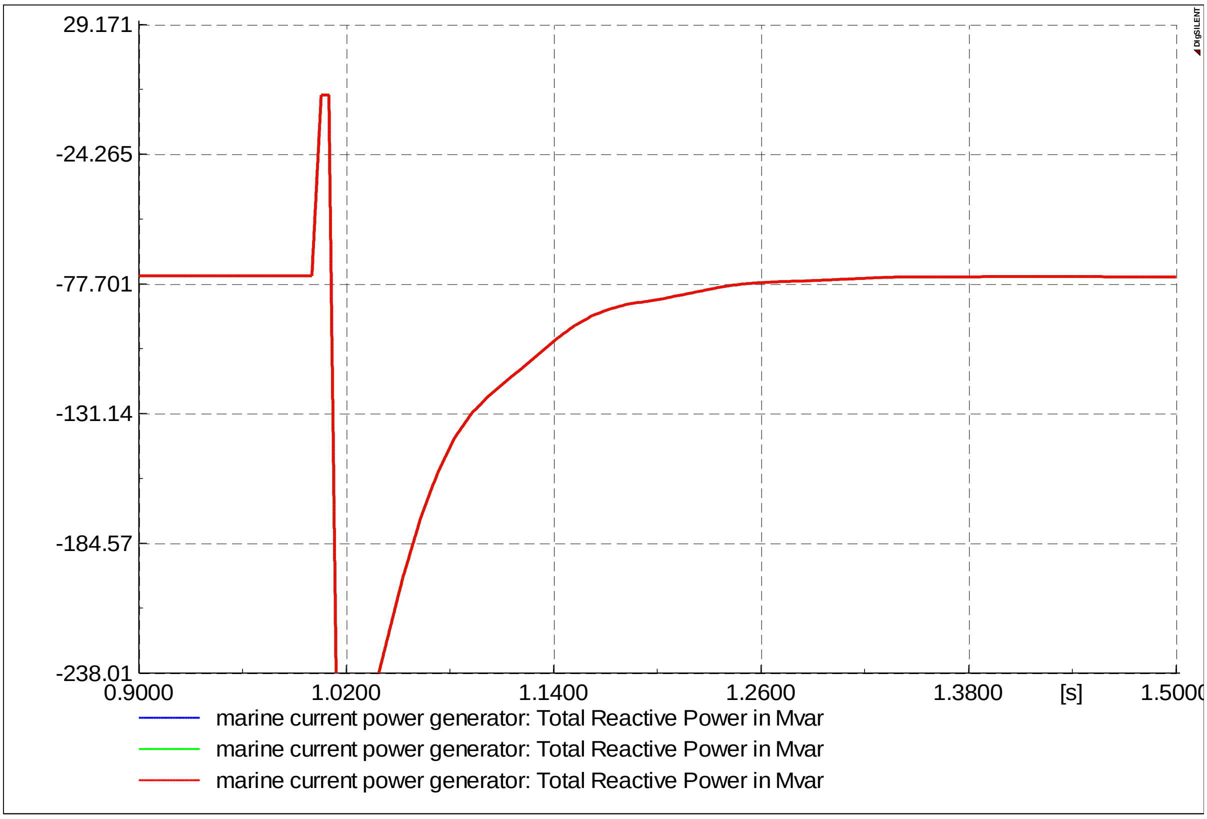


Fig 5.2 (e) Total reactive power of marine current generator connected to Grid with only HVDC Transmission line

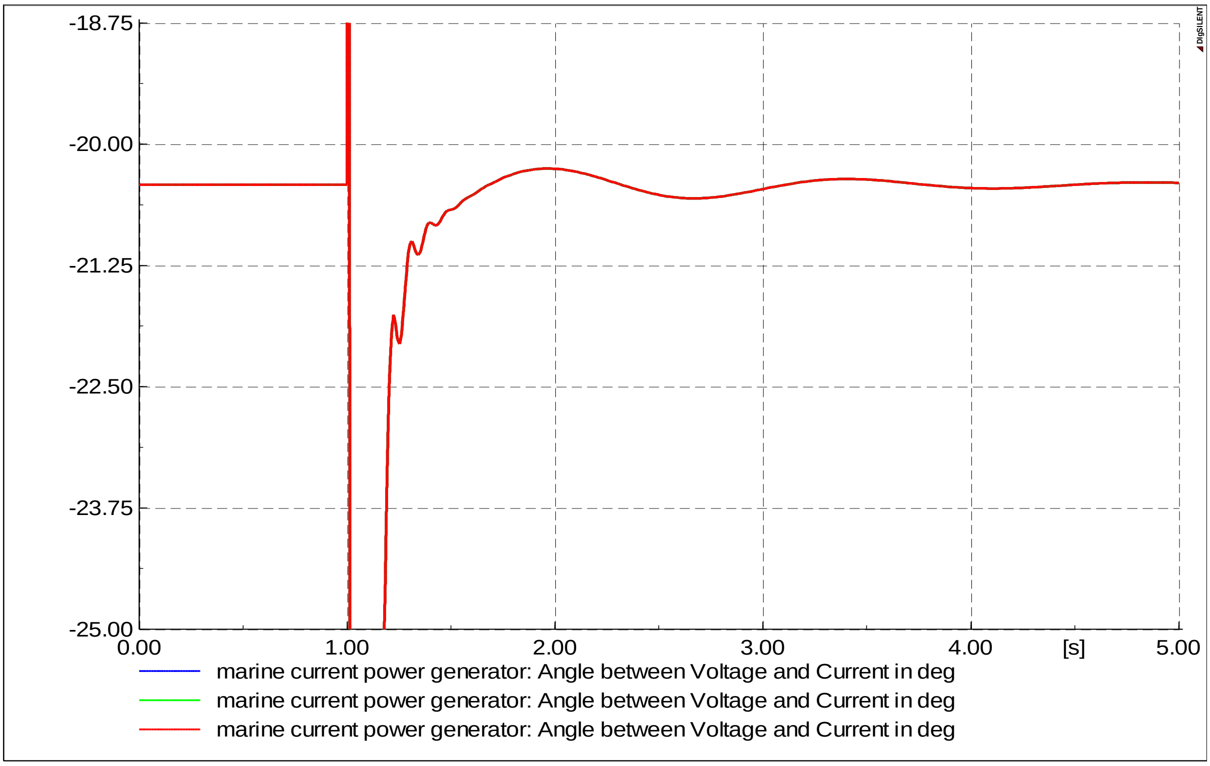


Fig 5.2 (f) Angle b/w voltage and current of marine current generator connected to Grid with only HVDC Transmission line

Performance of the marine current farm connected to grid when AC and HVDC both line has been present.

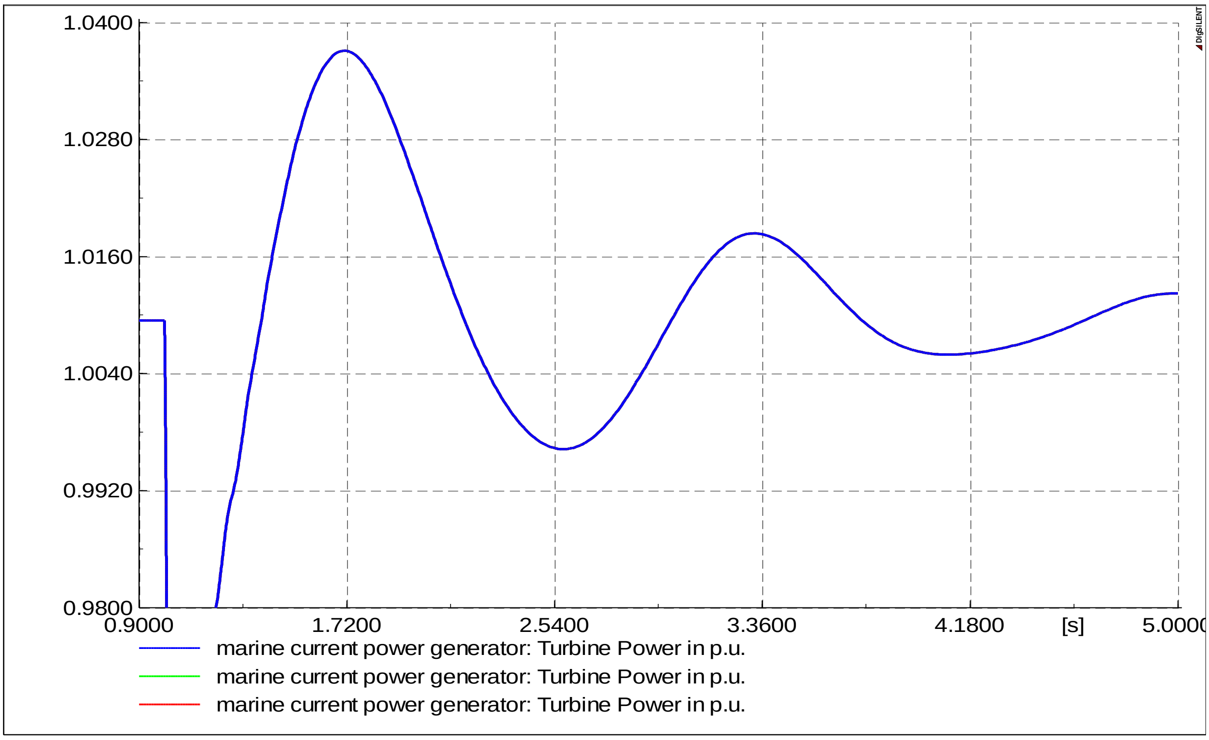


Fig 5.3 (a) Turbine power of MCT connected to Grid, when AC and HVDC both line has been present

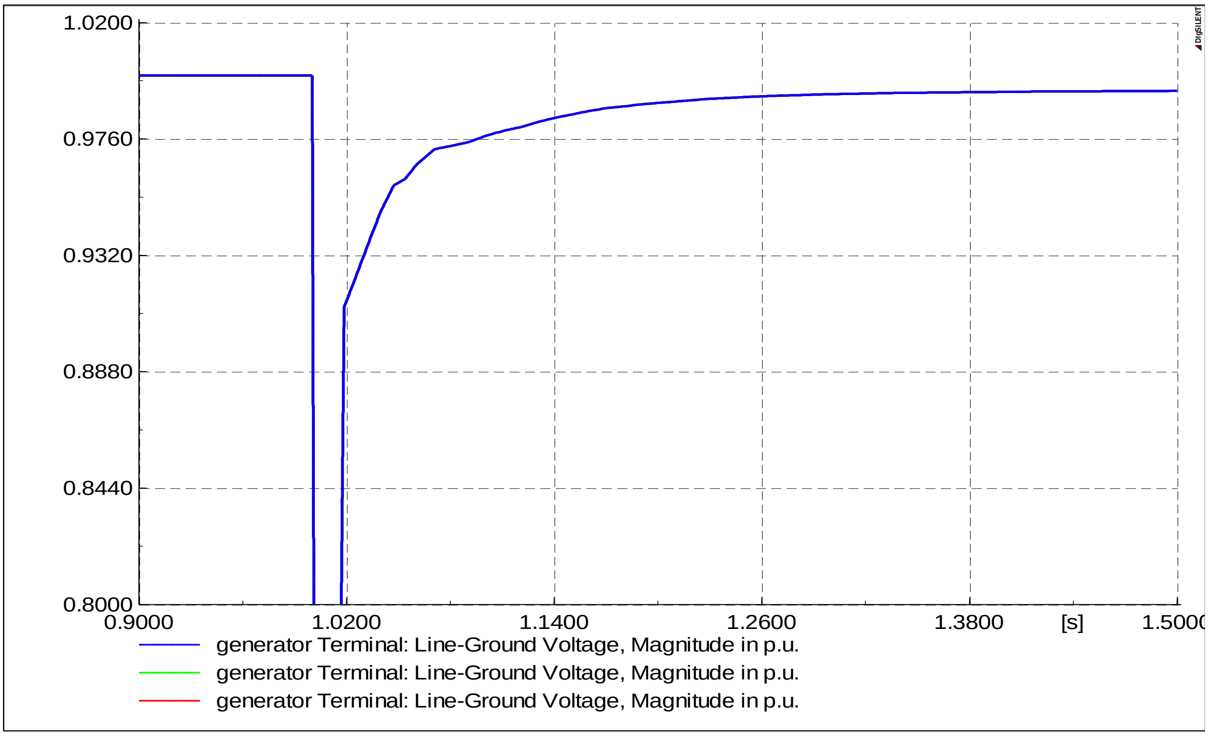


Fig 5.3 (b) Generator terminal voltage of MCT connected to Grid when AC and HVDC both line has been present

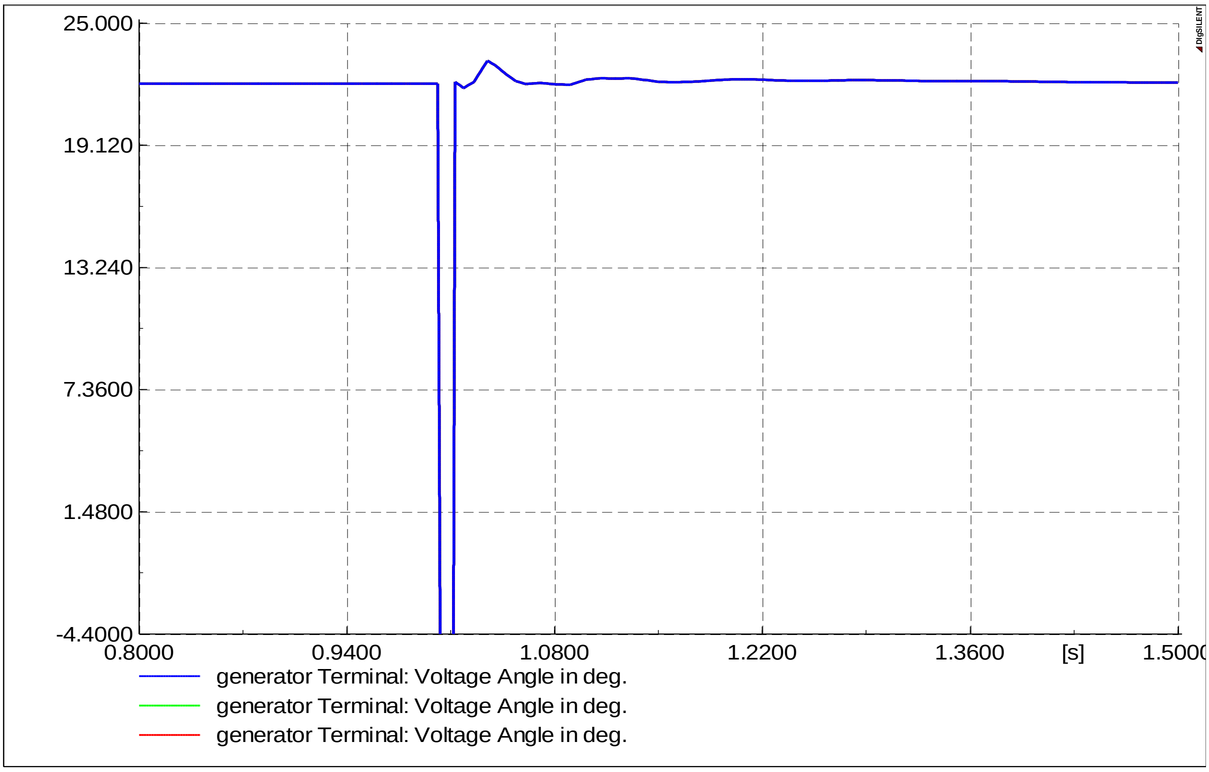


Fig 5.3 (c) Voltage-angle curve of MCT connected to Grid when AC and HVDC both line has been present

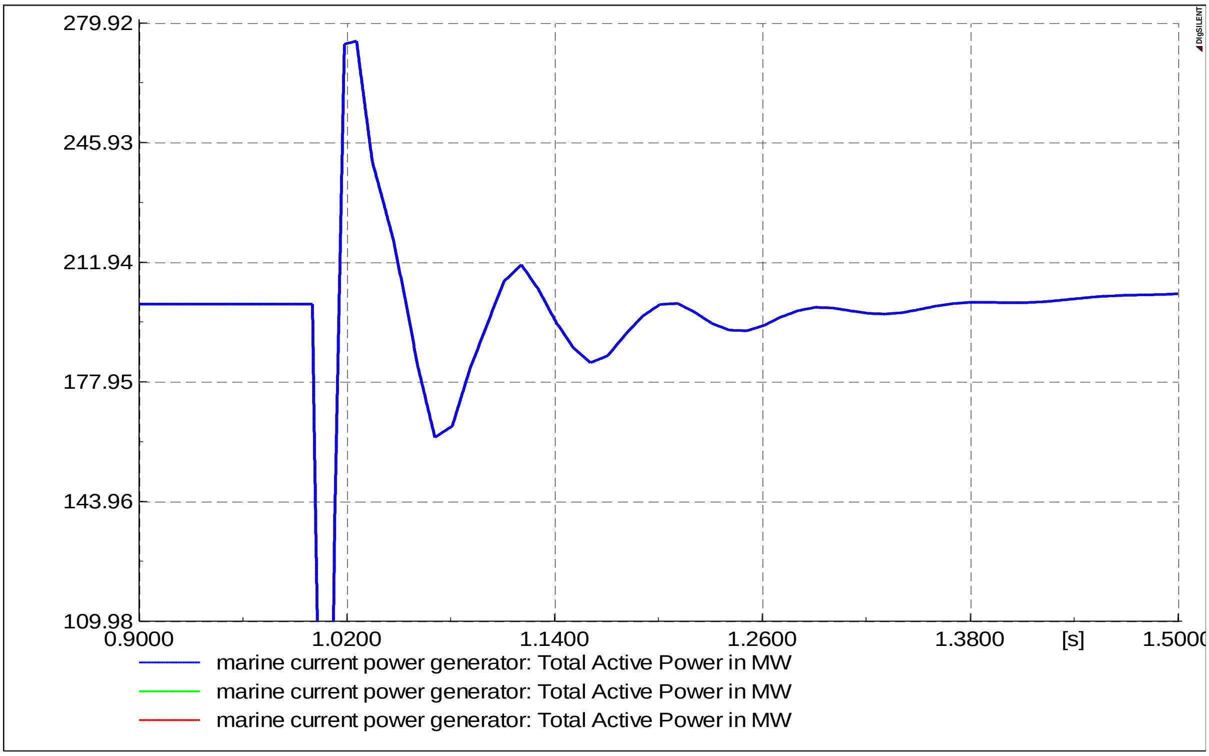


Fig 5.3 (d) Total active power of marine current generator connected to Grid when AC and HVDC both line has been present

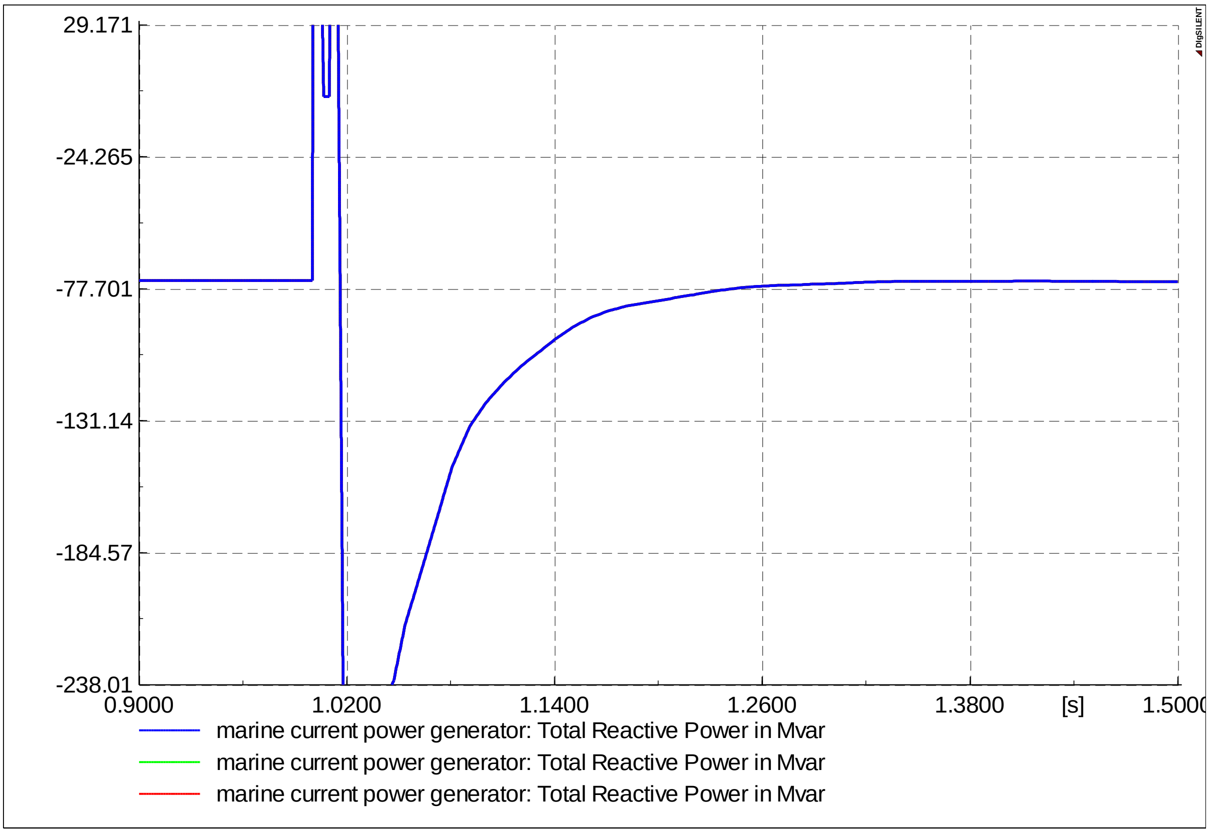


Fig 5.3 (e) Total reactive power of marine current generator connected to Grid when AC and HVDC both line has been present

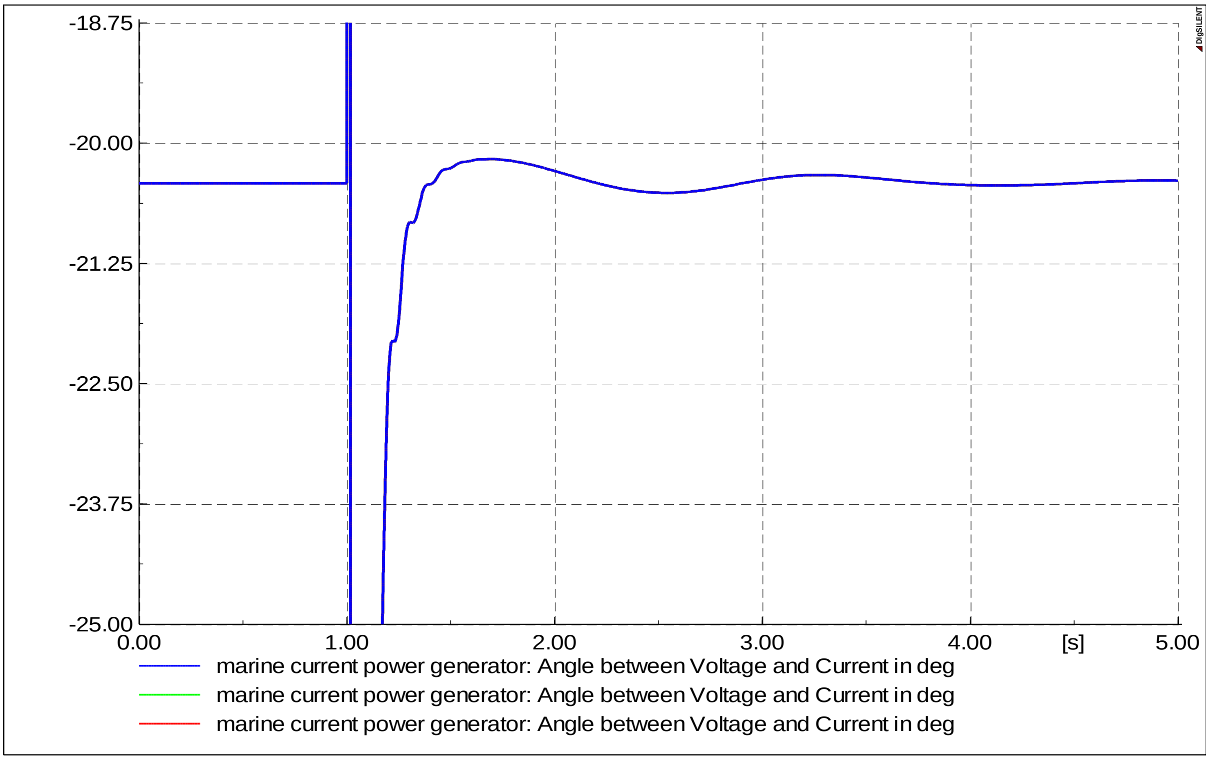


Fig 5.3 (f) Angle b/w voltage and current of marine current generator connected to Grid when AC and HVDC both line has been present

Performance analysis comparison of marine current farm connected to grid all the three cases.

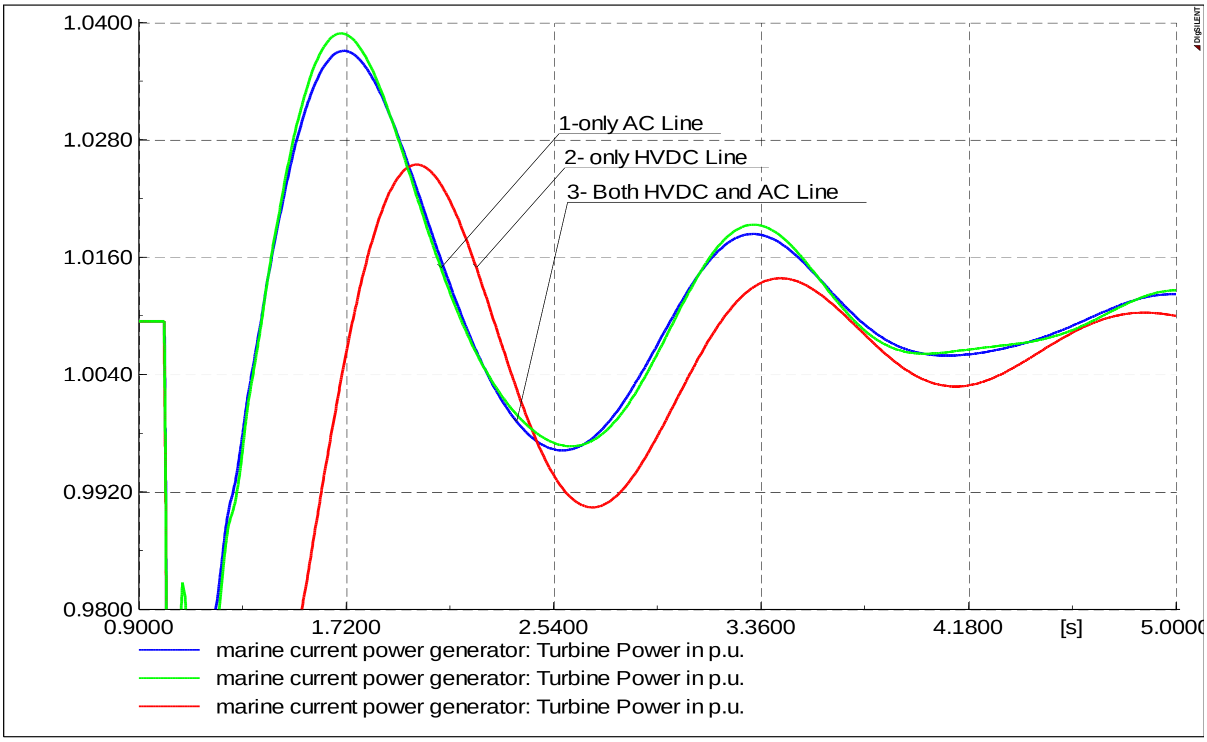


Fig 5.4 (a) Turbine power of MCT connected to Grid, comparing all the three cases

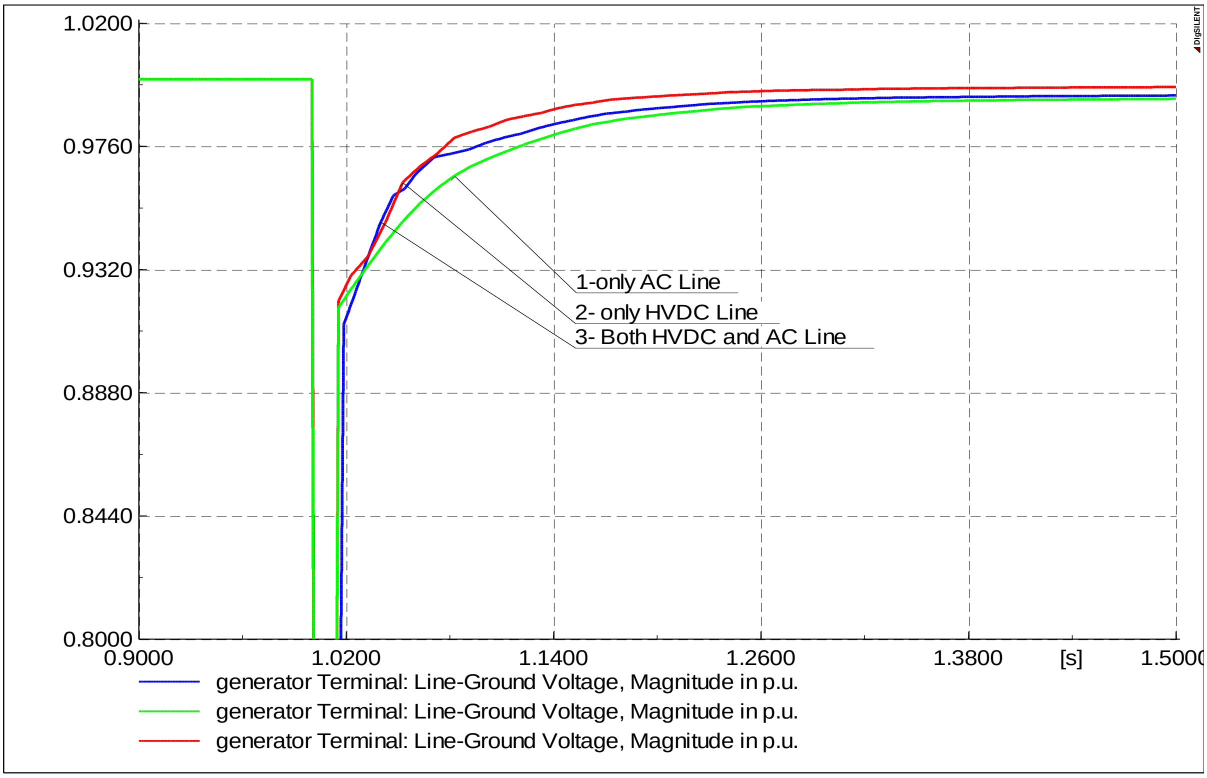


Fig 5.4 (b) Generator terminal voltage of MCT connected to Grid comparing all the three cases

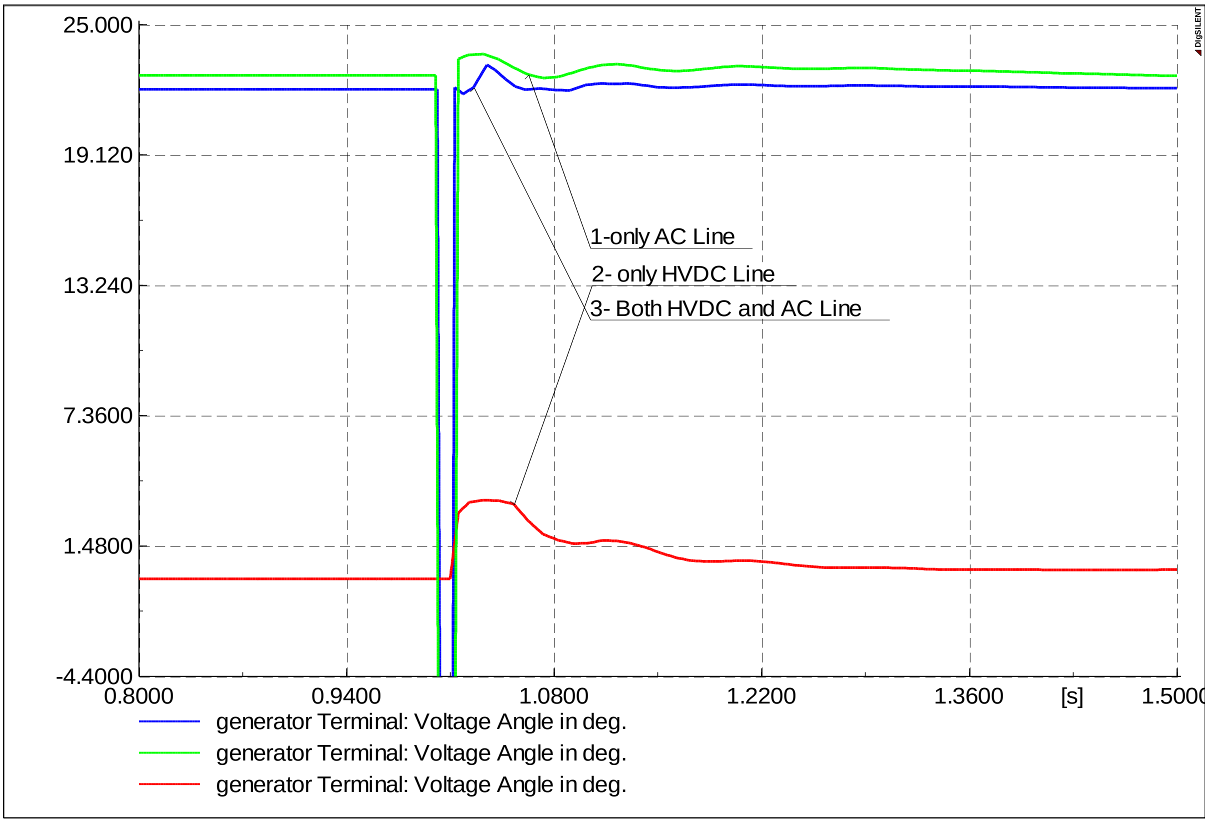


Fig 5.4 (c) Voltage-angle curve of MCT connected to Grid, comparing all the three cases

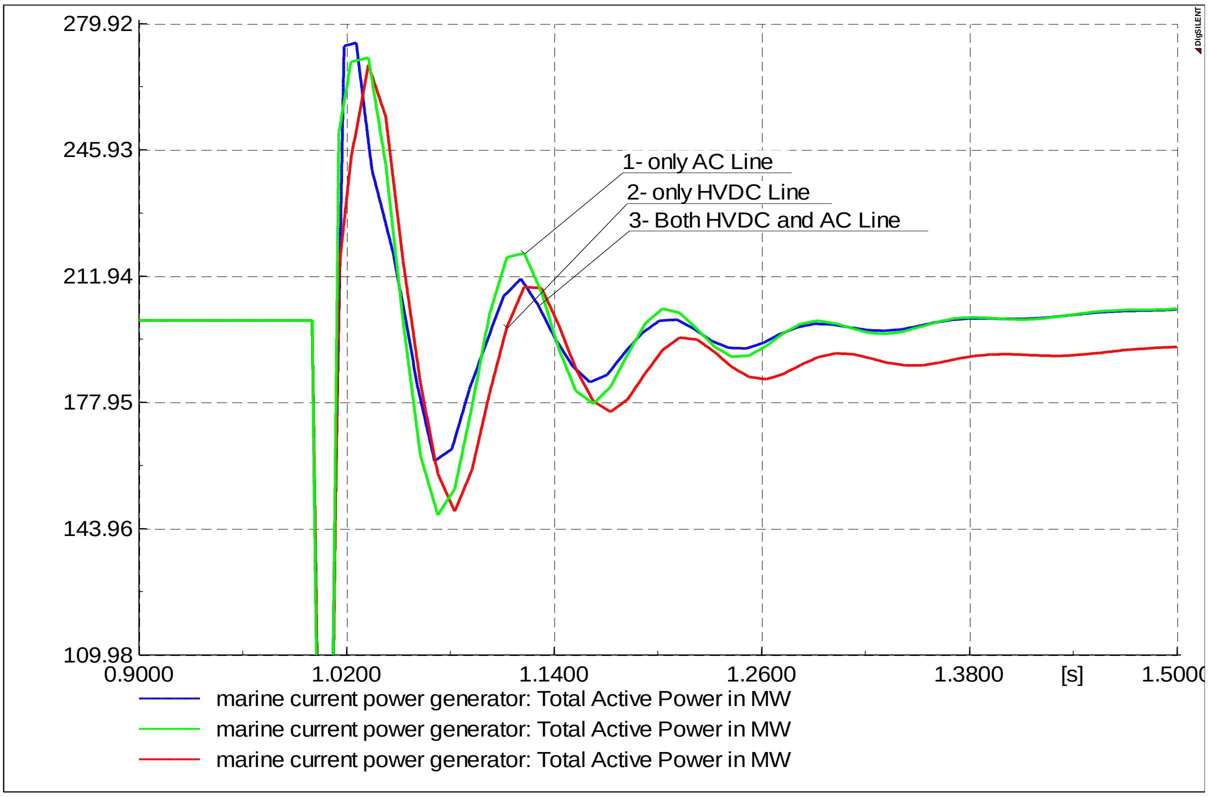


Fig 5.4 (d) Total active power of marine current generator connected to Grid, comparing all the three cases

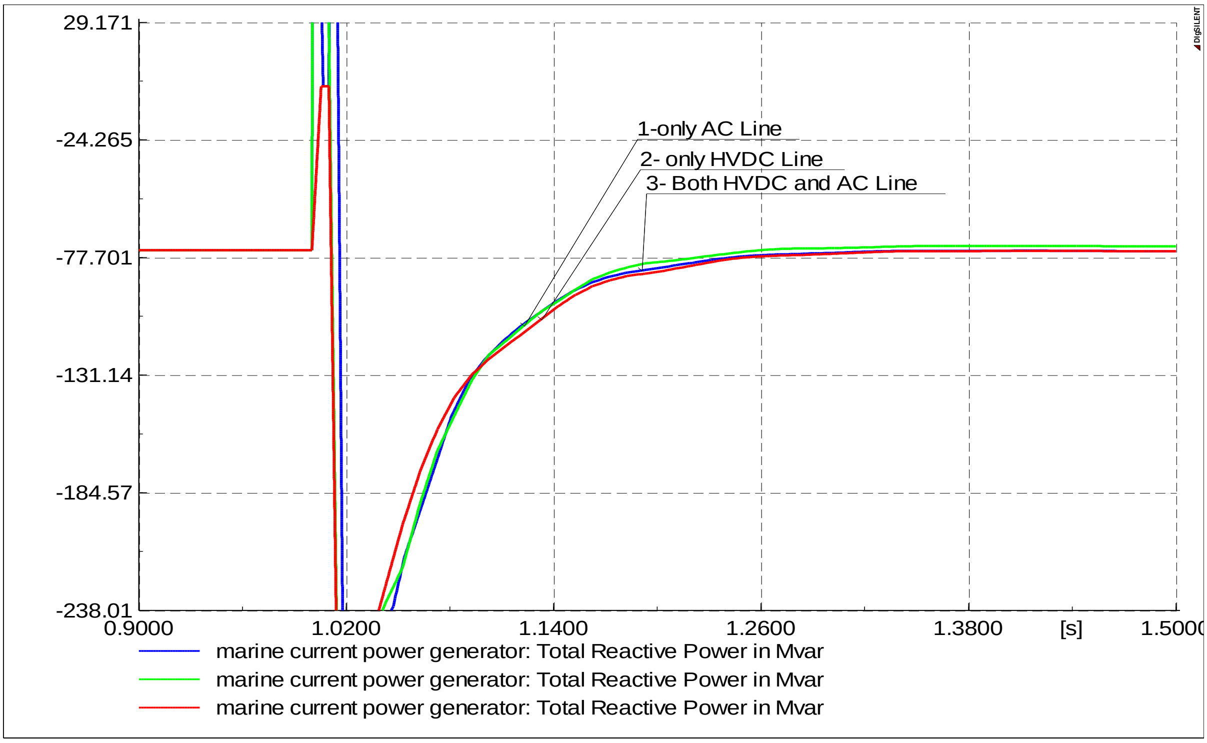


Fig 5.4 (e) Total reactive power of marine current generator connected to Grid, comparing all the three case

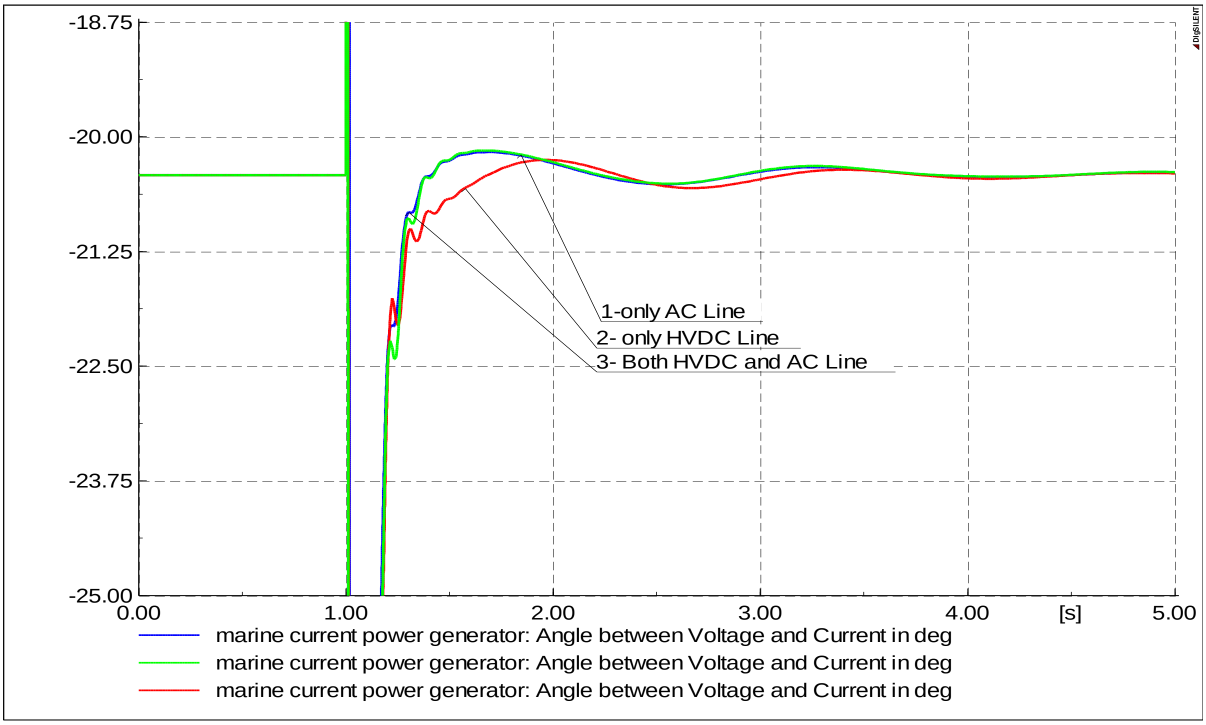


Fig 5.4 (f) Angle b/w voltage and current of marine current generator connected to Grid, comparing all the three cases

From Fig. 5.4 (a) to (f) it can be observed that terminal voltage, active power, rotor angle with mere AC transmission line the oscillations are large compared to the one with HVDC lines. An intermediate values is obtained when both AC and HVDC lines is connected.

From these figures it can be further observed that the recovery of MCF after the fault clearance is best if only HVDC link is considered. However it may lead to high investment cost.

From this analysis it can be further observed that connecting MCF to the grid directly through conventional AC transmission line shall result in comparatively large oscillations in the system leading to less stability margin. Further if only HVDC line is considered for full power transfer to improve the stability it may lead to local reactive power requirement by MCF.

It can be seen from this analysis that a combination of HVDC link and AC line can give a better option of improving the stability of MCF without very high investment cost for HVDC link.

CHAPTER 6
CONCLUSION & FUTURE SCOPE

6.1 CONCLUSION

This work has been mainly focused on the extraction and utilization of the marine current farm and also discusses the dynamic behavior of marine current farm connected to grid under different fault condition. Marine current is a vast source of renewable energy and mare predictable then the other farm of renewable energy. The extraction of marine energy on the same principle of wind energy but then power generated by marine current generator is much more as compare to the wind energy due to the density of water. Although not widely used in present but it is a future of renewable energy. Integration of the large scale array of marine current can produce huge amount of power and supply to the grid. The research has been continued in this area to make marine energy more efficient and cheaper

The entire study of a marine-current farm has been performed in time domain simulation with DIgSILENT powerfactory software. Performance of MCT during fault under three different configurations has been analysed. From this analysis it can be conclude that the stability of marine current form (MCF) is considerably improved with the presence of an HVDC Link.

6.2 FUTURE SCOPE

Marine energy is the one of the continuous available farm of renewable resources. It is the future of electricity generation. The research has been continued to utilize the kinetic energy of oceanic current and make it more feasible. The large scale integration of marine energy gives huge amount of power which can be supply to the industries for commercial purposes or for the domestic use. It is consider for clean electricity generation.

APPENDIX:

System Parameter:

Induction Generator:

$S = 2153\ KVA, V = 575\ V$
$r_s = 0\ pu, r_r = .01\ pu$
$x_s = .01pu,\ x_{rA} = .1pu, x_m = 4.0\ pu.$

AC Transmission line and transformers

$r_T = 0.0001059\ ohm/km,$
$x_T = 0.010802\ ohm/km$
x_t .575/11 KV, 2.5 MVA
x_T 11/240 KV, 200 MVA
$r_L = x_L$=0.001925 ohm/km

HVDC Transmission line

$v_{DC} = 250\ KV,\ s_{DC} = 200\ MW$
$\alpha_r = 15\ deg, \gamma_i = 15\ deg$
$T_r = T_i = 1, n_b = 2$

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LIST OF PUBLICATIONS

Satendra Kumar and S T Nagarajan "Stability Analysis of Off Shore Marine Current Farm Connected to Grid" *Proceeding of 2015 IEEE* International Conference on Technological Advancements in Power and Energy (TAP-Energy 2015), Amritapuri University held on 24-26 Jun 2015.