Steady state analysis on HVLF-AC transmission for offshore wind power by modern XLPE submarine cable

A Siva*
Asst. professor,EEE,MIET
Jaggaiahpet, AP, INDIA

L Jagannadham
Assoc. professor,EEE,MIET
Jaggaiahpet, AP, INDIA

P Lakshmi
PG student,EEE,JNTUK-UCEV
Vizianagaram, AP, INDIA

Abstract— This paper proposes a new breed of HVLF-AC transmission system for offshore wind power by modern submarine cable. The proposed HVLF-AC system offers increasing active power transmission capability and transmission distance compared with existing 50HZ HVAC submarine transmission system. The proposed system is integrated with the main power grid with a three phase 6 pulse bridge cycloconverter at receiving end side, and with 24 pulse converter at sending end side. Additionally, this paper investigates the steady state performance on proposed transmissions system. A 60MW wind farm was simulated in Matlab simulink and also perform FFT(Fast Fourier Transform) analysis of proposed HVLF-AC transmission is studied during steady state condition..

Keywords— Offshore wind power, Submarine cables, 24-pulse converter, 6 pulse bridge cycloconverter, FFT analysis.

I. INTRODUCTION

Over the last decades, non-renewable energy sources have been used as the main source of energy conversion into electric energy [1]. However, disadvantages of use of these non-renewable sources, the harmful on the environment and tending to increase in the long run and the cost subject to market instability. Recently, new innovation and technological development of renewable energy, especially energy from wind, expected for environmental impact reducing Carbon Dioxide (CO2) and maintenance [2]. Offshore wind power plants are an important component of the future electrical power generation due to greater space availability and better wind energy potential in offshore locations [3]. Presently, ongoing research on the integration of offshore wind power plants with the main power grid. For transmission of offshore wind power, well-established technologies are high-voltage ac (HVAC) and high-voltage dc (HVDC) [4].

HVAC transmission is advantageous compared to HVDC transmission because it is directly to design the protection system and to change voltage levels using transformers. However, the capacitance of submarine ac power cables high, which leads to high charging current, which, in turn, reduces the active power transmission capacity and limits the transmission distance(up to 50-75 km)[5]. HVDC transmission enables secure and stable asynchronous interconnection of power networks that operate on different frequencies [6]. In addition, HVDC provides instant and precise control of the power flow. Once installed, HVDC transmission systems become an integral part of the electrical power system, improving the overall stability and due to the absence of reactive current in the transmission line improves the active power transmission capacity and capability of distances greater than 100km for offshore wind power transmission [7].

In this paper, new breed of high voltage low frequency (HVLF) - AC transmission system for offshore wind power by modern submarine cable proposed. Besides HVDC and HVAC, an intermediate -frequency level (typically one third of fundamental frequency) is used for this proposed transmission system. The required frequency level is created using cycloconverter at receiving end. An appropriate modern submarine three-core cross-linked polyethylene (XLPE) power cable is selected for HVLF-AC power transmission. The selected XLPE cables have a conductor cross section adequate to meet the system requirements for power transmission capacity. The cost of energy losses can be reduced by using larger conductor. Load losses in XLPE cables are primarily due to the ohmic losses in the conductor and the metallic screen. XLPE cables can be loaded continuously to a conductor temperature of 90°C. The current rating of submarine cables follows the same rules as for land cables [8].

At the sending end of the proposed LFAC system, a 24-pulse thyristor-based inverter is used to generate low frequency (16Hz) ac power, as shown in Fig. 1. At the onshore substation (receiving end side), a thyristor-based cycloconverter is used as an interface between the low frequency side and the 50Hz onshore main power grid. Thyristor-based converters can transmit more power with increased reliability and lower cost compared to VSC-HVDC systems. However, large filters are necessary at both ends to suppress low-order harmonics and to supply reactive power. Furthermore, the system can be vulnerable to main power grid disturbances.

For AC transmission system, the active power (*P*) transmitting over the transmission lines, which should be cables for connecting offshore wind farms, which can be expressed by

$$P = \frac{V_S V_R}{X_L} \tag{1}$$

Where V_S-sending end voltage per phase and V_R-receiving end voltage per phase respectively. X_L is line reactance per phase. The above equation is valid for short submarine cable, which increasing transmitting power either by increasing the voltage level or lowering the impedance of the cable and neglects the effect of the line angle. Furthermore, reactance is proportional to power frequency f,

$$X_L = 2\pi fL \tag{2}$$

Where L is total inductance per phase over the transmission line, decreasing the electricity frequency can proportionally increase the transmission capability. In this proposed transmission system, power to be transmitted with low frequency, then increasing active power transmission capability and transmission distance compared with existing 50HZ HVAC submarine transmission system.

The paper is organized as followed: Section II presents the electric modelling of the proposed transmission system. Section III presents the control strategy for cycloconverter at receiving end side and inverter at sending side. Section IV presents simulations of a HVLF-AC transmission system, which demonstrate its response during steady state condition using the Matlab/Simulink language. Section V presents FFT analysis for main grid side voltage and current wave forms under steady state condition. Section V presents concluding.

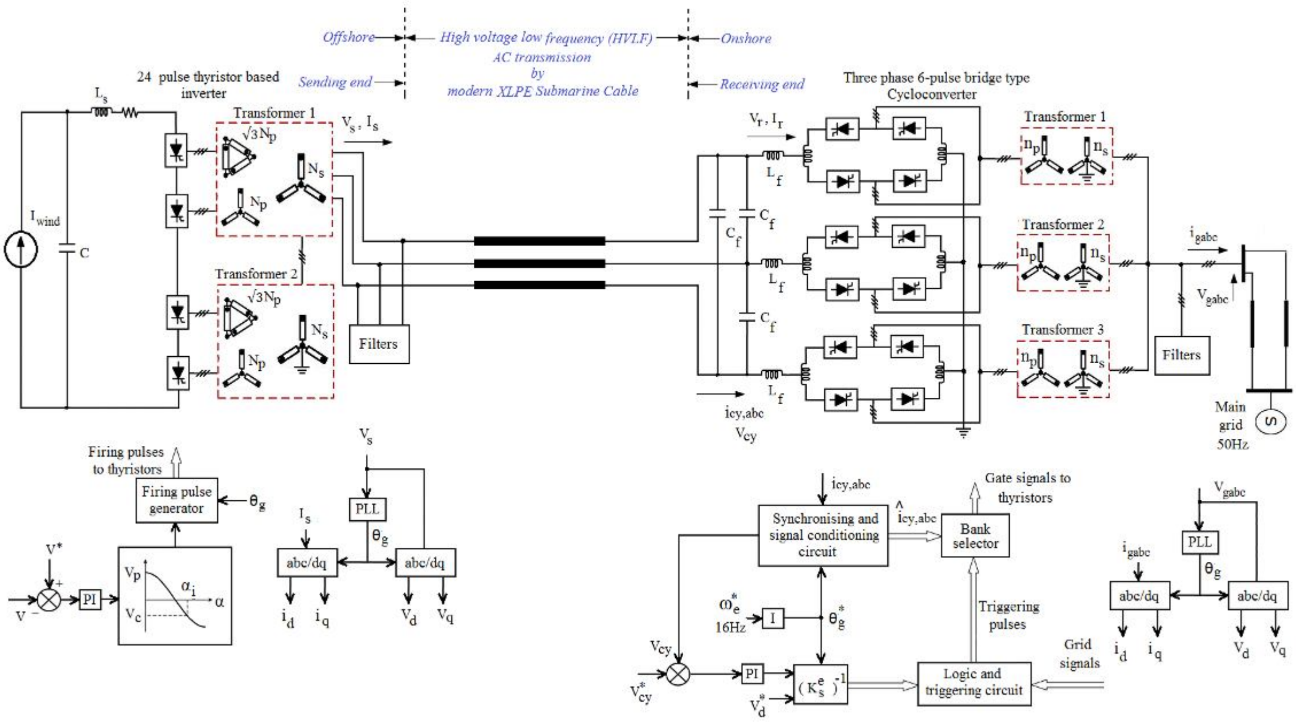


Fig. 1 Test network of Proposed HVLF-AC transmission system for offshore wind power

II. ELECTRIC MODELLING OF HVLF-AC TRANSMISSION SYSTEM

Fig.1 shows proposed high voltage low frequency (HVLF)-AC transmission system for offshore wind power by modern submarine cable. At the sending end, I_{wind} represents total power of 60MW, which is obtained by collecting rectified total ac output power of series connected wind turbines. A smoothing reactor is connected between inverter and current source I_{wind}. A 24-pulse inverter is used to convert dc power to an intermediate frequency level(16Hz) ac power and this inverter connected to a power transformer to increase voltage level. It increases voltage to higher level (132KV, line-to-line, rms) for high voltage transmission, but with the same rated current, 50Hz transformer derated by a factor of three i.e only 1/3rd of original rated voltage because power is to be transmitted under low frequency(one third of fundamental frequency). AC filters are used at both ends to reduce high order harmonic effect and supply the reactive power required by converter. At receiving end 16Hz ac power converted into 50Hz ac power by three phase 6 pulse bridge cycloconverter. Finally, 50Hz ac power fed to 50Hz main grid.

III. CONTROL SYSTEM

A. *Inverter Control Technique*

The control scheme at sending end side for the inverter is shown in Fig. 1. Presently, so many control technique approaches developed to designing the control scheme for generation of gate pulses at the required delay angle α_i. Most common approaches are: cosine wave crossing control, ramp comparator approach, equidistance pulse firing control and digital firing control [9]. In this paper, cosine wave control technique is used for the generation gate pulses at the required delay angle α_i.

The delay angle α_i is given by

$$\cos\alpha_i = \frac{V_C}{V_P} \tag{3}$$

Where V_C is the control voltage, V_P is the peak value at the cosine wave. The control voltage V_C is varied from V_P and -V_P to vary αi from 0 to π. The angular position θ_i of the ac-side voltage is provided by the phase-locked loop (PLL), θ_i is necessary for generation the firing pulses for the inverter. In this control technique, because of the linear characteristics, the response of the inverter closed - system improves.

B. *Cycloconverter Control Technique*

The control scheme at receiving side for the converter is shown in Fig.1. The main objective of the control scheme is to provide a 16Hz voltage. V_{CY} is the fundamental component of the cycloconverter 16Hz side voltage; it is obtained from the synchronising and signal conditioning logic shown in Fig.1. At receiving end side cosine wave control technique is used for the generation gate pulses.

A cosine modulating signal at input frequency is the best combination possible for comparison to derive the trigger signals for the SCRs. which produces the output waveform with the lowest total harmonic distortion[10]. The final cycloconverter output wave shape is composed of alternate half cycle segments of the complementary P-converter and the N-converter output voltage waveforms which coincide with the positive and negative current half cycles, respectively. gains for all of the controllers and test network parameters used in this paper are listed in Tables I–II.

TABLE I

XLPE cable parameters	Value
Cross section of conductor (mm^2)	500
Insulation thickness(mm)	18.0
Diameter over insulation(mm)	65.0
Lead sheath thickness(mm)	2.5
Outer diameter of cable(mm)	190
Capacitance (µF/km)	0.17
Inductance (mH/km)	0.40
Charging current per phase at 50Hz A/km	4.7
Rated current	655
Nominal voltage	150
Maximum voltage capability	175

TABLE III

Devices	Sending end side	Receiving end side
Transformer:		
Power rating	180MVA	180MVA
Voltage ratio	33KV/400KV	132KV/220KV
Per unit impedance	(0.0008+j0.32)	(0.001+j0.64)
Filters:	2000µF,0.05H	50mH, 6.7µF
Parameters of PI controller:		
K	1	0.125
τ	0.1	0.05

IV. PERFORMANCE EVALUATION

The proposed HVLF-AC transmission that uses a 24-pulse inverter and three phase 6-pulse bridge type cycloconverter investigated here. For the transmission, the voltage and frequency levels are chosen as 132KV and 16Hz. Transmission cable parameters are given in table I. To demonstrate steady state analysis of the HVLF-AC system, at t= 0.3s a load of 60MW in introduced at receiving end side, illustrating the voltage and current capability during network alteration. Fig.2 (a) active and reactive power exchange at inverter station. Fig. 2. (c) and (e) shows that high-quality voltage and current waveforms injected into HVLF-AC line with ac filters installed. Based on these results, proposed HVLF-AC transmission system is able to meet steady state requirements. Based on the same system parameters, for the proposed 16-Hz HVLF-AC system maximum transmission distance and sending - end power calculated, observed that the proposed transmission system can delivering the rated power over a distance approximately 3 times than the HVAC transmission. Typically, for distances longer than 100 km, HVDC systems are the preferred solution, but proposed HVLF-AC transmission system could be capable of transmit the power for the distance 100–200 km range.

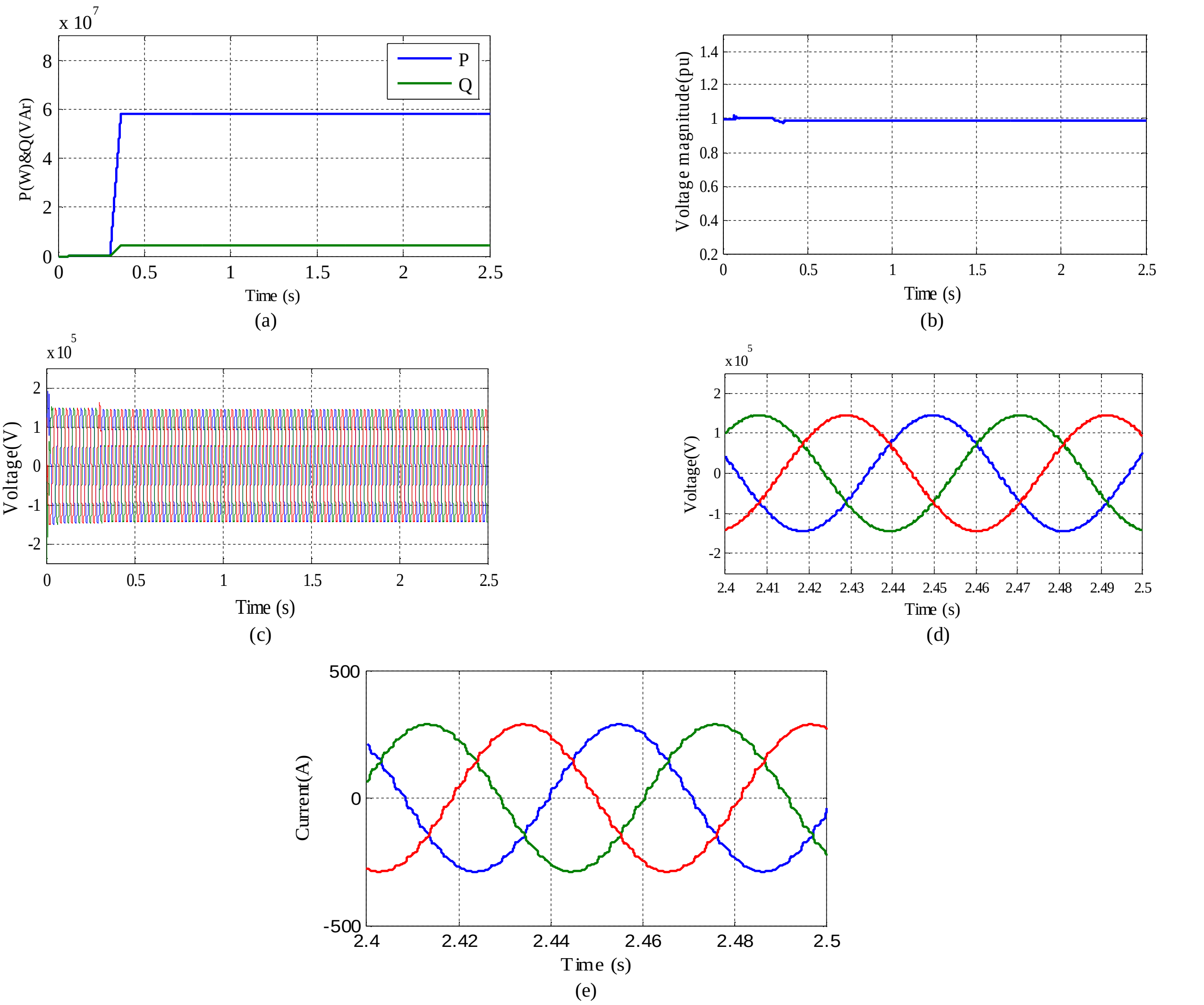
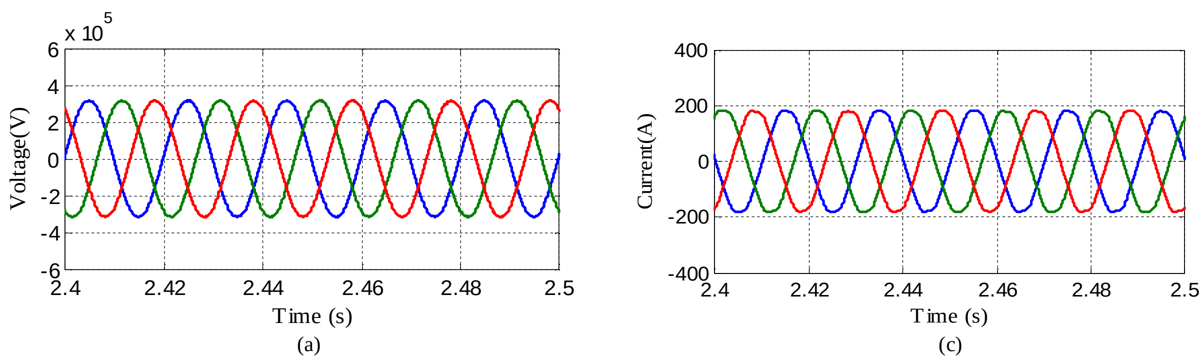
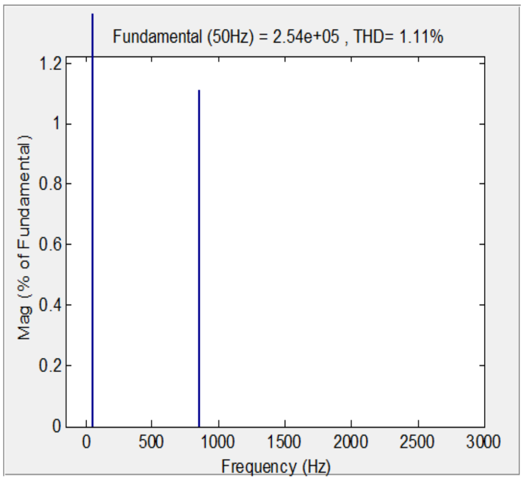


Fig. 3 Waveforms demonstrating the steady-state operation of HVLF-AC transmission system for offshore wind power by modern submarine cable. (a) active and reactive power at receiving end side; (b) voltage magnitude at sending end side transformer (c) voltage waveforms at sending end side transformer; (d). Zooming version of waveform in Fig. 2 (c); (e) current waveform injected into the transmission system.

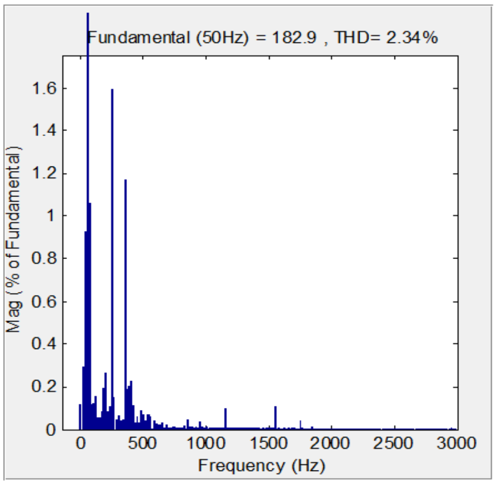
V. FFT ANALYSIS

A study based on FFT analysis of the 60MW wind power generation system was done using Matlab simulink and harmonics during steady state conditions were simulated. The voltage wave form at grid side under steady state condition is shown in Fig. 3 (a) and after FFT analysis THD 1.11% in Fig. 3(b). The current wave form at grid side under steady state condition is shown in Fig. 3 (c) and after FFT analysis THD 2.34% in Fig. 3(d).





(b)



(d)

Fig. 4. (a) Voltage wave form at main grid side; (b) FFT analysis for voltage wave form at main grid side; (c) Current wave form at main grid side; (d) FFT analysis for voltage wave form at main grid side.

VI. Conclusions

The HVLF-AC transmission system for offshore wind power by modern XLPE submarine cables has been proposed. Methods to design the control strategies and system's components has been discussed. Proposed system can improve the power transmission capability due to lower cable charging current and lower frequency transmission, proposed system to be a possible solution for the offshore wind power plants integration with main power grid over long distances, and it to be a alternative power transmission method over HVDC transmission systems in certain cases. Furthermore, this system easier to establish an interconnected HVLF- AC network to transmit bulk amount of power from multiple plants. A mode of 60MW wind far m was simulated in Matlab and FFT analysis of the proposed system during steady state condition was tested.

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