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# Performance Investigation on PMSG based Fractional Frequency Transmission Systems via XLPE cables for Offshore Wind Power

***Abstract:*** - Presently, the research on Fractional Frequency Transmission System (FFTS) is fastened for the megawatt Offshore Wind Farms (OWF). FFTS has an ability to overcome the problem of charging current presented in the HVAC transmission and will effectively serve as an alternative to the traditional transmission systems. The basic structures and characteristics of a typical PMSG-based FFTS via XLPE cable for offshore wind power system is proposed and described first. Then the technical performance of power transmission through XLPE cable is evaluated by comparing the different cables such as flat and trefoil formation. Simulation results showcase notable enhancements in power transfer capacity, decreased power losses, and improved performance of control schemes. The feasibility studies describe the performance of FFTS (16.67 Hz) via trefoil cable is superior than FFTS flat formation cable transmission.

***Keywords:*** FFTS, Trefoil, Flat Formation, XLPE Cables and WT.

## 1. INTRODUCTION

In the realm of electrical power transmission, the choice of frequency plays a pivotal role in determining the efficiency, reliability, and economic viability of the entire system. While High Voltage Alternating Current (HVAC) transmission has been the conventional norm, the exploration and implementation of FFTS have gained significant attention in recent years. It, typically operating at frequencies below the standard power system frequency of 50-60 Hz, presents a unique set of advantages and challenges that have sparked interest among researchers and engineers alike. The FFTS emerged as a novel option, initially proposed in 1994 [1]. It was used to deliver the hydro power of distance around 2000 km [2]. This paradigm made shift towards FFTS is driven by the pursuit of enhanced efficiency, reduced transmission losses, and the ability to cover longer distances with fewer infrastructure investments.

Currently, Mega Watt (MW) wind farms are equipped with Type-4 wind turbines represent a cutting-edge design characterized by a full-power converter placed at the offshore platform rather than the nacelle. This innovative architecture enhances the efficiency, reliability, and overall performance of OWF. As the wind energy industry seeks to optimize energy production, reduce maintenance costs, and navigate the complexities of harsh marine environments [3].

Moreover, Cross-Linked Poly Ethylene (XLPE) cables are gaining popular as compared to the conventional ones for the offshore power transmission. This transformative technology has not only redefined the standards of insulation materials but has also revolutionized for the power transmission systems. As on this exploration of XLPE cables, it is essential to explore for the offshore wind power transmission with FFTS. However, the inherent limitations of these materials in terms of thermal stability, longevity, and overall performance spurred the quest for an advanced alternative [4]. Hence, a technical analysis needs to be carried out for offshore PMSG based FFTS through XLPE cable. There is lot of space in research for the XLPE cable.

For offshore wind power transmission, PMSG based FFTS through XLPE cable is more favorable due to the following reasons:

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1) The PMSG wind turbines can produce power within the frequency range of 12 Hz to 18 Hz without requiring a gearbox due to its low-speed design [5, 6].
2) FFTS offer a cost-effective solution for long-distance power transmission compared to HVAC due to lower initial investment costs, reduced maintenance needs, and minimized power losses over extensive transmission distances. Specifically, HVAC do not exceed 50 km distance due to challenges associated with submarine cables, as detailed in reference [7].
3) HVDC technology, despite its potential for long-distance transmission, faces economic and technical hurdles. For OWF, the power converters at both ends are costly and challenging to maintain particularly. Comparisons with FFTS in [8] highlight these issues, alongside with difficulties in DC fault management for VSC HVDC systems.
4) Implementing PMSG-based FFTS using XLPE cables appears no technical difficulty. As FFTS have already been successfully deployed in the railway grids, leveraging existing industrial knowledge. Additionally, it can easily form a network like a conventional HVAC does [9].

In this paper, the PMSG based FFTS through XLPE cable is chosen to transmit the offshore wind power to the onshore grid. The performance of power transmission is evaluated by comparing the flat and trefoil formation of XLPE cables and used time domain simulations to validate the results.

This paper is organized as follows. Section II, demonstrates the schematic diagram of PMSG based FFTS via flat and trefoil XLPE cables and its control. Section III. represents the detailed models of the cables and modelling equations of its losses. Section IV describes the PMSG based FFTS via XLPE Trefoil and Flat formation implementation in PSCAD/EMTDC and its performance evaluation using the time domain simulation. Finally, Section V concludes the paper.

## 2. SYSTEM CONFIGURATION AND CONTROL

A wind farm of 180 MW rated PMSG based FFTS is modeled in PSCAD/EMTDC. The OWF connected to 16.67 Hz onshore grid via 16.67 Hz step-up transformer and XLPE cable. The PMSG utilized in the Wind Turbine (WT) system, employing a full converter configuration, generates FFAC power [10]. The full converter serves as a frequency converter, comprising a Machine Side Converter (MSC), a DC link, and a Grid-Side Converter (GSC). The MSC and GSC interface with the PMSG and the offshore LFAC grid through a low-frequency transformer, respectively. The MSC optimizes power extraction from the PMSG while ensuring maintenance of the generator terminal voltage. Concurrently, the GSC regulates the d-q currents of the grid to maintain a constant DC link voltage.

For the comparative performance analysis, the two types of cables such as Trefoil and Flat formation type are modeled and connected to the onshore low frequency grid. In Fig.1, shown the schematic block diagram of the proposed PMSG based FFTS via Trefoil/Flat cables. The Trefoil/Flat XLPE cables are having the higher amount of power transfer capability.

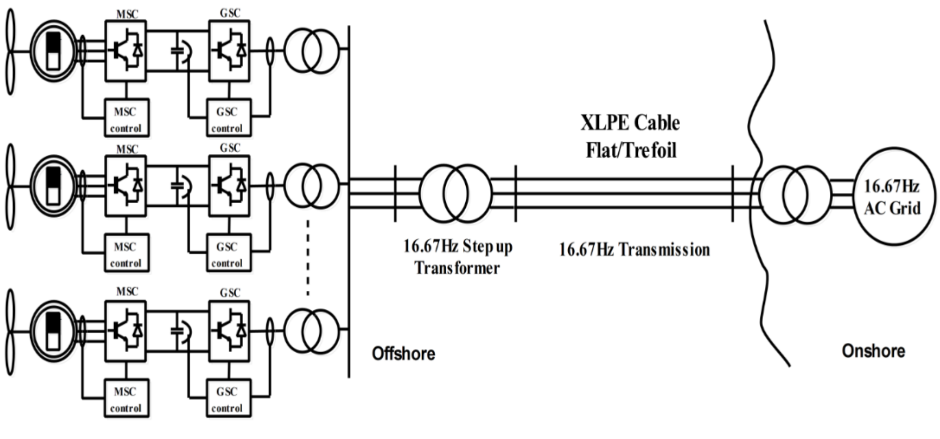



**Fig. 1. Schematic diagram of offshore wind power transmission via FFTS Trefoil/Flat type XLPE Cables**

### 2.1 General Control of MSC

The MSC control is employed for regulating the voltage and active power at the terminals of the machine due to the variable speed nature of the PMSG. Terminal voltages ($V_{abc}$) serve as reference values for phase angle generation through a Phase Locked Loop (PLL). Park's transformation is employed to convert voltage and currents into d and q axis quantities for the voltage controller. The modelling of the blocks such as d-q transformation, PLL and PWM is outlined in [9]. A PLL generates the reference signal for the voltage control block, which in turn provides the reference signal for Sinusoidal Pulse Width Modulation (SPWM), facilitating control over the switching of the MSC. The general control diagram of MSC is shown in Fig. 2.

### 2.2 General Control of GSC

The GSC control is a part of Type-4 WT, serving as the interface between WT and the offshore electrical grid. These converters play a crucial role in regulating voltage, frequency, and power quality to ensure stable and reliable grid operation. By employing sophisticated control, GSC can adjust reactive power exchange to maintain offshore grid voltage within specified limits, regulate active power output to support grid frequency stability, and mitigate harmonics to enhance power quality. The GSC is responsible for sustaining a stable DC voltage at the DC link of the Back-to-Back converter and connects to FFAC. The general control of GSC is shown in Fig. 3. This strategy involves comparing the actual DC link voltage and the reactive power of transmission with their respective reference values to derive the current order limit ($I_{dqord}$). A voltage control loop generates the reference voltage signal for SPWM switching, thereby regulating the firing angles of the GSC to control the output voltages effectively.

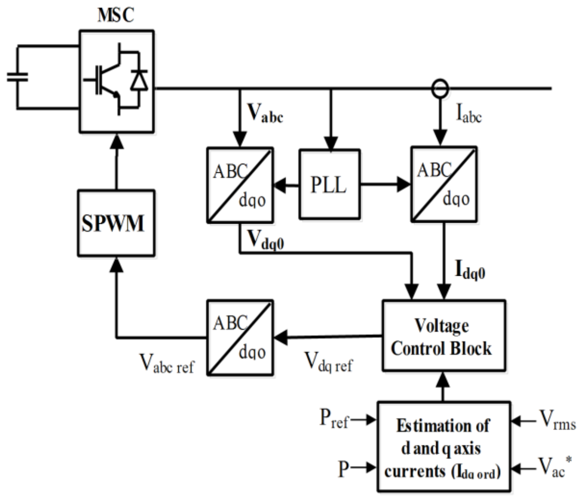



**Fig. 2. General control of the MSC**

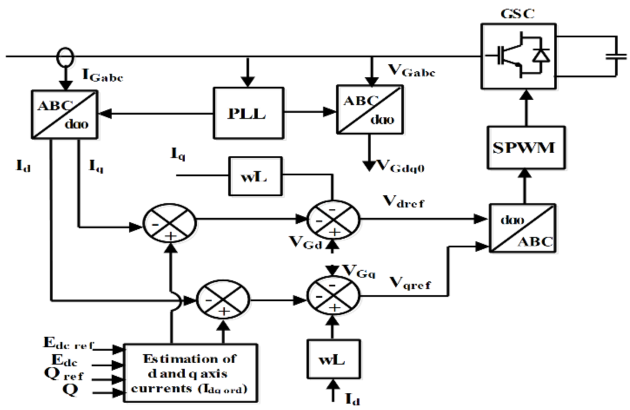


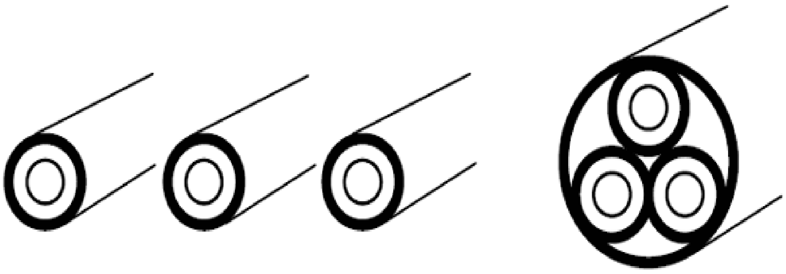

**Fig. 3: General control of GSC**

## 3. MODELLING OF CABLES and ITS LOSSES

### 3.1 XLPE Transmission Cables

In the modern days, the multi-MW offshore farms are installed in a certain distance to the shoreline. It requires efficient and higher rating cables [11, 12]. Henceforth, the technical and practical limitations need to investigate on the long AC XLPE cables. Hence, this section deals with some practical and electrical aspects of cable installations. There are two broadly classified types of XLPE cables. One is Flat formation and another is trefoil type [13, 14]. There are several solutions are required in detail on FFTS via XLPE trefoil/flat formation type which has not done in the literature. Therefore, a 132 kV XLPE trefoil/flat formation type cable is considered to address the feasibility study of both type cables.

In a three-phase circuit, the three cables are arranged in different formations, which are flat formations and trefoil (triangular). The selection of cable is subjected to several factors like conductor area, screen bonding method and space availability for installation [15]. Two different cables are considered for the analysis. The foremost one is Flat formation, where the three phases are separated and the later one is trefoil formation, where the three phases are bundled together shown in Fig. 4 (a) & (b) respectively [16].



**(a)** **(b)**

**Fig. 4. Two XLPE cable types (a) Flat formation (b) Trefoil**

The most distinct electric components in the OWF are single core submarine XLPE cables. The 132 kV three-phase single core submarine cable geometric dimensions for both flat formation and trefoil are given in Table 1. In the single core submarine cable, the conductor diameter is 37.9 mm, thickness of insulation is 15 mm, and diameter over the insulation is 71.3 mm which includes the conductor diameter and insulation thickness. Therefore, the overall outer diameter of the cable is 86.4 mm [14]. An economic solution for FFTS is the cable configuration.

**Table 1. Geometric dimensions of the 132 kV single core cable for both Flat formation and Trefoil type**

| Parameter | Value |
|---|---|
| Cross section of conductor | 1000 $[mm]^2$ |
| Conductor diameter | 37.9 [mm] |
| Thickness of insulation | 15 [mm] |
| Diameter over insulation | 71.3 [mm] |
| Cross section of screen | 95 $[mm]^2$ |
| Outer diameter of cable | 86.4 [mm] |

### 3.2 Cable Loss

The key components of OWF architecture are collection network and submarine cables. The 33 kV rated cables are used to connect the generator and collector transformer. The 33 kV cables are tapered with three different cross-sectional areas are used to transfer the generated power to the offshore low frequency substation, from collector transformer to onshore grid, 132 kV rated transmission cables are used. The cable charging current ($I_c$) decreases with reducing frequency and is calculated from Eqn. (1).

$$I_c = 2\pi f l C V \tag{1}$$

The resistive losses $P_\Omega$ per meter are calculated with Eqn. (2).

$$P_\Omega = I^2 R r_{AC} \tag{2}$$

where I is per phase current in A, $R_{AC}$ is AC resistance (Ω/m)

The cable's AC resistance comprises the DC resistance and caused from skin and proximity effects. Due to skin effect, the skin depth increases which results in the increased cross-section of the conductor at low frequency levels. For three-core cables, the skin effect multiplication factor is defined in the IEC-60287 standard which is calculated using Eqns. (3) and (4) [17].

$$y_s = \frac{x_s^4}{192 + 0.8 x_s^4} \tag{3}$$

$$x_s^2 = k_s \frac{8\pi f}{R_{DC}} \times 10^{-7} \tag{4}$$

where $y_s$ is multiplication factor of skin effect, $k_s$ is 1 for round conductors, $R_{DC}$ is DC resistance.

The proximity effect limits current distribution in nearby conductors, causing an increase in effective conductor resistance. This arises from induced eddy currents proportional to current flow in each conductor. Eqns. (5) and (6) define the proximity factor for three-core cables, quantifying this effect in accordance with standard practices.

$$y_p = \frac{x_p^4}{192 + 0.8 x_p^4}\left(\frac{d_c}{s}\right)^2 \left[0.312\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\dfrac{x_p^4}{192 + 0.8 x_p^4} + 0.27}\right] \tag{5}$$

$$x_p^2 = k_p \frac{8\pi f}{R_{DC}} \times 10^{-7} \tag{6}$$

Where, $y_p$ is multiplication factor of proximity effect, $k_p$ is 1, s is distance between the conductor axes in mm and dc is diameter of the conductor in mm.

The total $R_{AC}$ losses can be obtained from Eqn. (7).

$$R_{AC} = R_{DC}\left(1 + \left(y_s + y_p\right)\right) \tag{7}$$

The dielectric insulation material decides dielectric losses of the cable. For a single-phase cable dielectric loss $W_d$ under AC operation is shown in Eqn. (8).

$$W_d = 2\pi f C\, V^2 \tan\delta \tag{8}$$

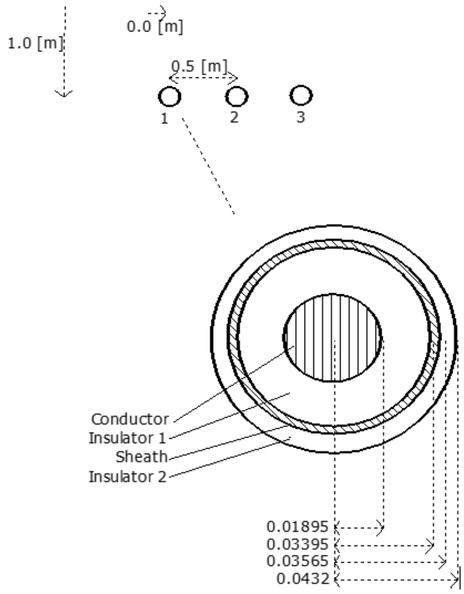
where tan δ: loss factor of insulation (XLPE-0.0004).

### 3.3 Modelling of Flat Formation and Trefoil Type Cables

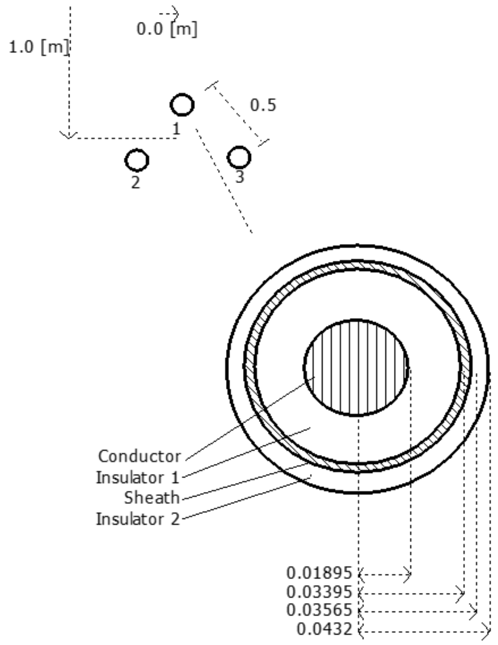
The 132 kV transmission voltage level is considered for FFTS. The single/three-core XLPE copper conductor submarine power cable is selected [18, 19]. The nominal and maximum voltage levels of the cable are 132 kV and 145 kV respectively. The cable's resistance is 17.6 mΩ/km, inductance, and capacitance are 0.35 mH/km and

0.25 F/km respectively. In Figs. 5a and 5b, shown the Flat formation and Trefoil geometric configuration of the medium voltage submarine cable and are modeled in PSCAD/EMTDC. Using the frequency dependent model, the 132 kV XLPE cables are modeled which characterizes the frequency dependence of internal transformation matrices.

A constant wind speed of 11.3 m/s is considered for the analysis. Each WT connects to the grid after 1.2 sec of the delay for the synchronization of grid. The MSC is responsible for constant DC link voltage which is shown in Fig. 8. At beginning, the grid transmits the power to the wind turbines. As the generator attain the speed at a constant value, after 1.2 sec the WTs will connect to the offshore grid. While synchronization, power direction switching induces a small effect on DC link voltage. Hence, MSC control initiates to optimize wind power extraction while stabilizing generator terminal voltage.




**(a) Flat formation cable**




**b) Trefoil cable**

**Fig. 5. The geometric configuration of flat and trefoil cables modeled in PSCAD/EMTDC**

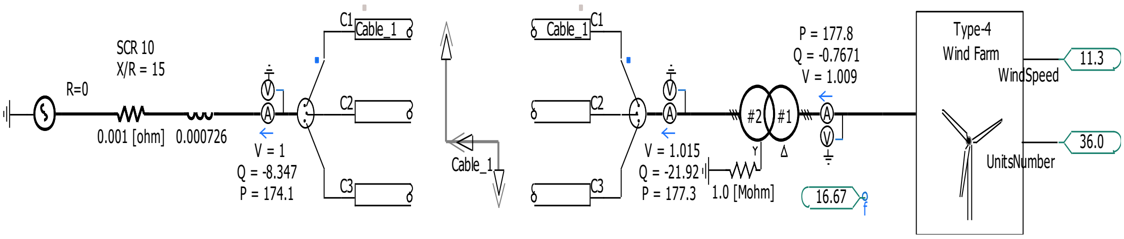



**Fig. 6. 180 MW of PMSG based FFTS via Flat formation or Trefoil XLPE cable implemented in PSCAD/EMTDC**

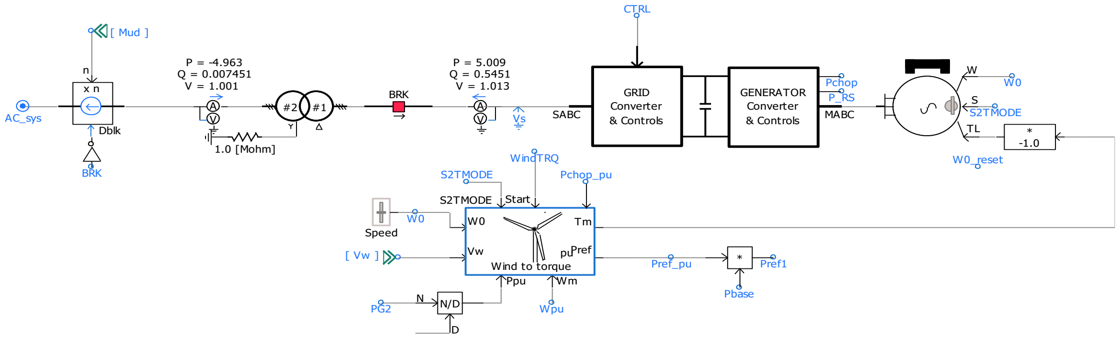



**Fig. 7. 5 MW Type-4 wind turbine implemented in PSCAD/EMTDC**

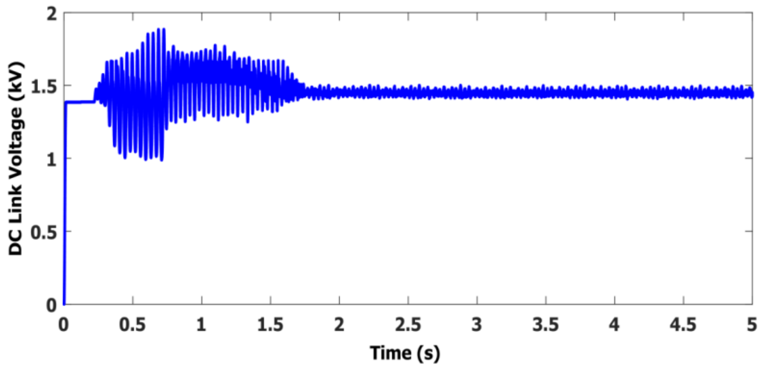
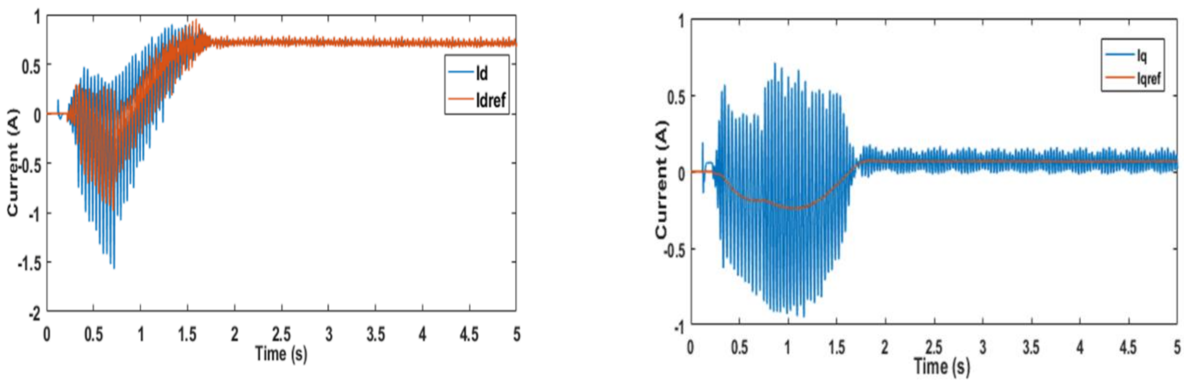



**Fig. 8 DC-link voltage**

Fig. 9(a)&(b) depicts the active and reactive current components for a frequency of 16.67 Hz respectively. The active current component exhibits no steady variation within the system, while the reactive component remains at zero, but with desirable damping oscillations. The peak value of the d component ($I_d$) adheres to the designated reference value in the dq controller, with the actual value closely tracking the reference signal within the dq controller.




(a) (b)

**Fig. 9 (a) Reference $I_d$ compared to actual $I_d$ in dq controller**

**(b) Reference $I_q$ compared to actual $I_q$ in dq controller**

In Fig. 10, the power transfer capability of both flat formation and trefoil type FFTS is illustrated. It is observed that trefoil cable has transferred the higher amount of active power than the Flat formation cable because of its minimum net inductance. This is due to the symmetrical spacing between the conductor axes. The entire simulation is done up to 400 km length line.

The power loss comparison for both Flat formation and Trefoil type XLPE cables over the length up to 400 km is shown in Fig. 11. The transmission power loss in case of flat formation type is slightly higher than the trefoil type. The flat formation cable is drawing more amount of reactive power because of its higher inductance. The higher inductance is due to the asymmetrical spacing between the conductor axes. Moreover, the higher inductance is also reducing the current carrying capacity of the cable and induce the eddy currents in the cable sheath and metallic conduits.

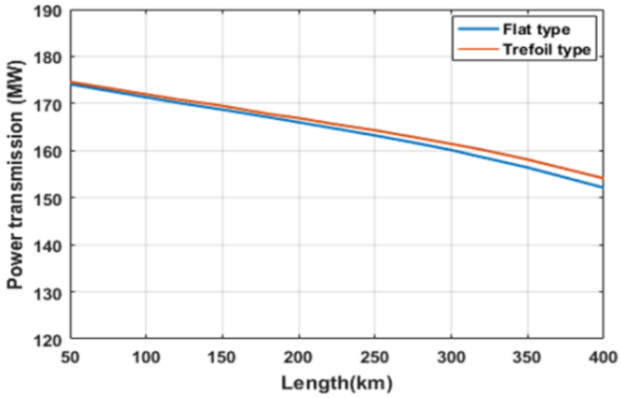



**Fig. 10. Power transfer capability of both Flat formation and Trefoil type FFTS**

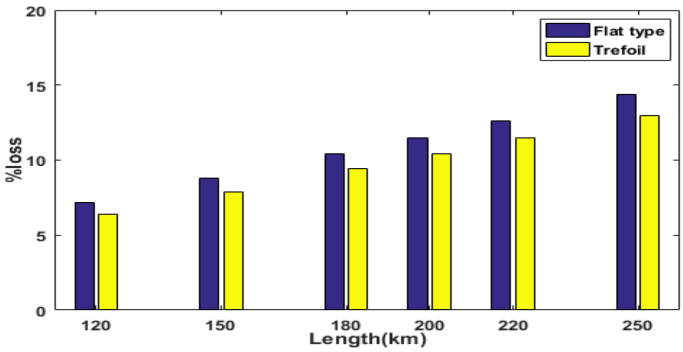



**Fig. 11. Power loss comparison between the both Flat formation and Trefoil type FFTS**

In Fig. 12, shown the active and reactive power transmission via FFTS Trefoil XLPE cable at a length of 120 km. It is observed that, up to 1 sec the power is transferred from grid to WT. At steady state condition (1.7 sec), almost 171 MW of active power is transmitted at 16.67 Hz frequency, whereas 14 MVAR of reactive power has taken by the line. The grid currents at 16.67 Hz shown in Fig. 13. Up to WT stable time (t=1.7 sec) is reached, the grid currents are having high harmonic content and oscillating nature. The peak value of current is 1.2 kA. In Fig. 14, shown the grid voltages at FFTS end. It shows the control system performance, because it meets the grid codes such as frequency and phase angle.

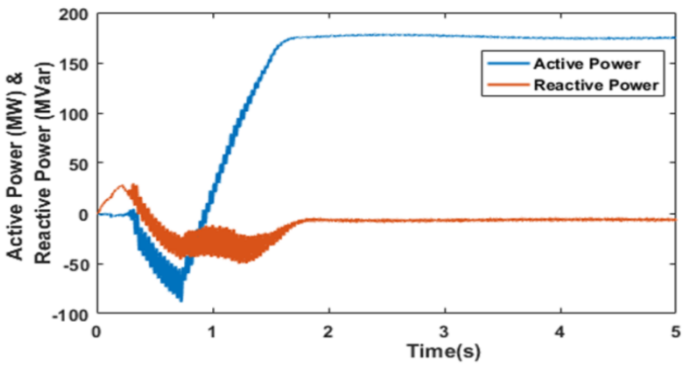



**Fig. 12 Active & reactive power transmission of Trefoil cable at 120 km distance**

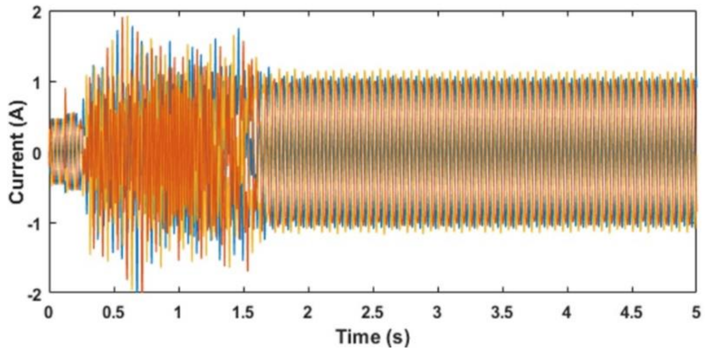



**Fig. 13. Grid currents**

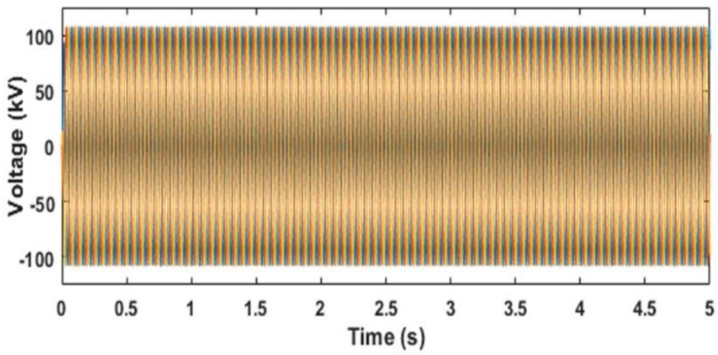



**Fig. 14. Grid voltages**

## 4. CONCLUSION

The PMSG based offshore wind power transmission via 132 kV FFTS via flat formation and trefoil XLPE cables is proposed and implemented in PSCAD/EMTDC. A comparative analysis on FFTS via Flat formation and Trefoil type XLPE cable has been presented. The control strategies of MSC and GSC have been developed to maintain the terminal voltage of PMSG and constant DC link voltage respectively. It is worth noting that, two XLPE cables are capable of exporting power of 150 - 155 MW over a 400 km distance at 16.67 Hz frequency. On comparing, the trefoil type gives more favorable cable parameters in terms of high active power transmission, low power loss and less amount of reactive power. As a future scope, there are no barriers to connect the proposed XLPE trefoil cable for FFTS to the onshore 50Hz grid with BtB Voltage Source Converter.

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