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A New Frequency for Offshore Wind-farm based on Component Loss Calculation

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Abstract

Offshore wind power plants are gaining importance in recent years, as there is adequate space available for its installation, high wind speed, no restriction on the size of turbine blades (no transportation and construction problem) and blades can be allowed to rotate at higher speed without any noise constraint, thereby increasing the rated power. However, the existing offshore wind farms face greater cost related challenges than those of onshore plants. The integration of offshore wind farm with onshore power grid is a complex issue. Feasible solutions for power transmission through cables from offshore wind farms to onshore are HVAC, line commutated HVDC and VSC-HVDC. This paper analyses the various schemes for integration of offshore wind farm with onshore power grid and suggests that LFAC with submarine cable operating at 0.7 Hz is an optimal choice in obtaining better performances.

Index Terms: offshore wind farms, low frequency ac transmission, HVDC Transmission.

I. INTRODUCTION

In recent years, the focus on electrical power generation from renewable sources, such as wind, solar and hydro energy is gradually increasing as the technology is simple and easy to use. As a consequence of rising fossil fuel prices, advanced technology has facilitated the power consumers to opt for small roof top wind turbines to generate power for their usage, thereby reducing their power tariffs and CO_2–emissions. Besides they are able to sell excess power to the service provider by connecting their lines to the grid.

The kinetic energy of the wind is converted into mechanical energy by the turbine using the way shaft and gear box, which are arranged in such a way that different operating speeds convert this mechanical energy into electrical energy. Wind is unreliable non-conventional energy source and the output of wind turbine is not constant by which output power from the wind farm is not consistent but fluctuating. Due to this instability of generator output, it’s not suitable for the generator to connect directly to the grid. Hence, it is necessary to use a controller to manage the output produced by the wind turbine generator. Offshore wind farms are likely to be source of future electric generation due to ample space availability and better wind speed. In particular, transmission of electric power from offshore to onshore grid has become challenging task to electrical/power engineers.

At present high voltage AC (HVAC), high voltage DC (HVDC), low frequency AC (LFAC) transmission system are well known technologies for transmission as shown in Fig. 1. HVAC is advantageous because of its simple design, availability of circuit breakers and transformers. However, the charging current of AC submarine cable due to large capacitance is high and reduces the active power transmission capacity and limits line distance from offshore to onshore. The HVAC is thus recommended for relatively short underwater transmission of distance less than 60Km from offshore plant to onshore.

There exists two classes of HVDC depending on the type of power electronics devices used. The former class involves line commutated converter HVDC (LCC-HVDC) using thyristors and can transmit power up to 1GW with high reliability [1], while the later one employs voltage source converter HVDC (VSC-HVDC) using self commutated devices like IGBT'S [2]. The major advantage of HVDC is no limitation on transmission distance due to absence of reactive current in the cable. In addition to HVAC and HVDC, low frequency AC transmission has been recently proposed [3]-[4].

The various schemes for integration of offshore wind farm with onshore power grid have been discussed and analysed in this paper. From the discussions, it has been suggested that LFAC with submarine cable operating at 0.7 Hz is an optimal choice in obtaining better performances.

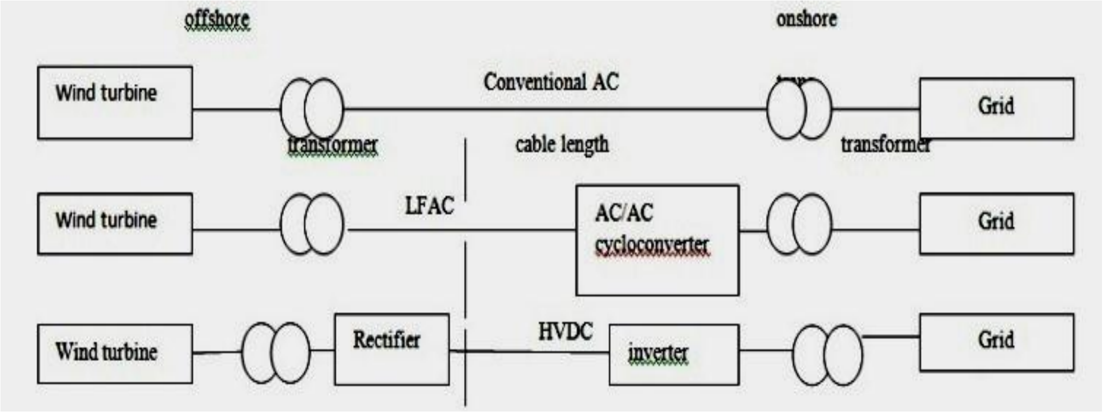


FIG: 1 Offshore wind energy transmission technology available

II. TECHNICAL SOLUTION FOR OFFSHORE POWER TRANSMISSION

As the transmission links using overhead lines, towers and air insulation conductors are impossible in offshore transmission system, submarine cables are suggested as a solution. However, the charging current of submarine cables at 50Hz operating frequency limits the transmission distance up to 100-120 km. Longer transmission may result in higher reactive current in the cable which in-turn limits the available active power transmission capacity. The only alternative solution for HVAC has been HVDC transmission, which is very costly due to expensive converters at both sides DC link. Moreover, larger number of devices and lower life time of the equipments on sea increase the operational expenditure. The proposed scheme thus transmits power through submarine cable at lower frequency of 0.7Hz, which requires one back to back frequency converter at onshore, demanding less maintenance. However, the lower operating frequency makes the transformers and shunt reactors larger and heavier due to the larger core area at the same allowable flux density. The proposed scheme enables linking of different offshore and onshore grid voltages and reduces environmental effects due to the use of converter components only at onshore. The proposed scheme is developed for single phase supply.

III. COMPONENTS AVALIABLE FOR LOW FREQUENCY TRANSMISSION.

A. *Submarine Cable*

The standard AC submarine cables, available with a voltage rating up to 400 kV and operating frequency of 50/60 Hz, can be used in the proposed scheme for operation at 0.7 Hz. The use of the standard submarine cable at lower operating frequency increases the thermal rating of the cable under normal environmental conditions due to lesser sheath and dielectric losses, and smaller cable resistance due to lower skin effect [12].

B. *Power Transformer and Shunt Reactor*

The 50 Hz, single phase transformers with ratings up to 187.5 MVA and primary voltages up to 145 kV weigh around 200 tonnes. The transformer, designed with an objective of weight reduction for operation at a frequency of 0.7 Hz, will weigh at least four to five times of those of 50 Hz transformer. The shunt reactors for operation at 0.7 Hz will also be too bulky with larger weight.

C. *Frequency converter*

The offshore wind farm connected with LFAC system requires a frequency converter or a variable frequency transformer [5-7] at onshore side. The proposed scheme considers line commutated cyclo-converter involving line commutated thyristors or IGBTs as a frequency converter for operation at 0.7/50Hz because of its lower cost. The scheme does not require any converter at offshore side, thereby resulting in lower investment, running and maintenance costs.

IV. COMPONENT LOSS CALCULATION

Power transmission through AC underground cables is limited by the capacitive charging current I_c which is almost 15-20 times greater than that of overhead lines and is given by

$$I_c = \frac{2}{\sqrt{3}} \pi \, f_n C \, l \;\; amps \tag{1}$$

where f_n denotes the transmission frequency, C indicates capacitance per km and l represents the length of the cable.

Due to this charging current, dielectric loss plays a vital role in long distance offshore wind farm power transmission and is given by

$$P_{Dloss} = 2\, f_n V_n^2 \, C \, l \tan \delta \;\; \text{watts} \tag{2}$$

where, V_n is the nominal voltage.

Hence it is necessary to switch on shunt reactors on both ends of the submarine cable. The capacity of reactors is calculated usually with the nominal voltage and frequency according to the following equation.

$$Q_C = \pi \, f_n V_n^2 \, C \, l \;\; \text{vars} \tag{3}$$

The copper loss depends on the length and resistance of the cable which in turn depends on the area of cross section of cable and skin effect.

$$P_{Culoss} = I^2 (R_c \, l) \; \text{watts} \tag{4}$$

$$R_c = \frac{\rho \, l}{A} \tag{5}$$

$$Skin\ depth = \frac{1}{\sqrt{\pi \, f_n \sigma \mu}} \tag{6}$$

Where, I is the transmission current, R_c is the resistance of the cable per km, ρ is the resistivity, A is the cross section area of the cable, μ is the permittivity and σ is the conductivity.

In a single core power transmission cable, normally a metallic sheath is coated outside the insulation layer to prevent the ingress of the moisture, protect from mechanical change, serve as an electrostatic shield and act as a return path for fault current and capacitive charging current [8-9]. When an isolated single conductor cable carries alternating current, an alternating magnetic field is generated around it. When the sheaths of single-conductor cables are bounded to each other, the induced voltage causes current to flow in the completed circuit. This current causes losses in the sheaths and reduces the cable capacity. The sheath loss of the cable is given by:

$$P_{sh} = I^2 \frac{(2\pi \, f_n)^2 (M_{sh} I)^2}{R_{sh} I} \tag{7}$$

Where R_{sh} is the sheath resistance, M_{sh} mutual inductance between a core of one cable and the sheath of an adjacent cable given by

$$M_{sh} = \frac{u}{2\pi} \ln\left(\frac{d}{r}\right) \tag{8}$$

Where, d is the distance between core of the cable, r is the radius of the cable. Hence, total loss of the AC submarine cable is given by the sum of Dielectric loss, Cu loss and sheath loss.

The Steinmetz equation is the classical method to calculate transformer core loss which is given by

$$A_c = \frac{V_n}{\sqrt{2}\,\pi\, f_n N B_m} \tag{9}$$

$$P_{ct} = A_c A_w k\, f^{\alpha} B_{pk}^{\beta} \tag{10}$$

Where, A_c is transformer core area, P_{ct} is the transformer core loss, N is the number of turns of transformer, B_m is flux density and α and β are constant whose value depends on the core material of the transformer.

V. PRINCIPLE OF LFAC TRANSMISSION SYSTEM

A. *Power Transmission through Submarine Cable*

Active power transmitting (p) over the transmission lines i.e cables for connecting offshore wind farms can be given by

$$P = V_S V_R \sin\left(\frac{\delta}{X}\right) \tag{11}$$

Where, V_S and V_R are the sending and receiving end voltage respectively X is line reactance, and δ is the transmission angle. The above equation is valid when the cable is short in length that neglects the effect of the line angle [10-14].

From equation (11), it is clear that the power depends on voltages and reactance of transmission line. Power transmission increases either by increasing voltage or by decreasing reactance of transmission cable. With fixed sending and receiving end voltages, the only way to improve transmission capability is by reducing the reactance, which dominates the line impedance, of the cable through reducing the operating frequency.

$$X = 2\pi\, f_n\, L \tag{12}$$

Where, L is the total inductance over the cable, decreasing the electricity frequency can proportionally increase transmission capability. The LFAC system based on this concept is not only able to increase the transmitting power but also improve the voltage stability given by

$$\Delta V\% = \frac{QX \times 100}{V^2} \tag{13}$$

Where ΔV is the voltage drop over the cable, V is the nominal voltage and Q is the reactive power flow through the cable. As the recatance/impedance is reduced in LFAC system due to reduced frequency the voltage drop over the cable is proportionally reduced [15].

B. Frequency Range

The Operating frequency of LFAC system depends mainly on two factors: the first one is the space charge accumulation in the cable and the second one is the harmonics generated by the line commutated 3 phase cyclo-converter. The frequency of the LFAC system should be set lower than 1/3 of the conventional nominal frequency to reduce harmonics [13]. Feasible Operation frequency range for 50 Hz system is given by

$$0.1 < f_n < 50/3 \text{ Hz} \tag{12}$$

In this paper, 0.7 Hz frequency is used for transmission to study the LFAC system.

C. Cost Comparison

The total cost comprises the investment cost and the running cost. The investment cost is the cost associated with the terminal equipments and cables [11]. As shown in Fig (1), the conventional HVAC system has offshore and onshore transformers, whereas LFAC transmission contains additional cyclo-converter. The VSC-HVDC transmission system needs two more converter stations, one at offshore and another at onshore. Even though LFAC system needs frequency converter with minimum of 36 thyristors, the total terminal cost of LFAC is comparatively lower with VSC-HVDC as converter cost in HVDC is quite costly. Moreover, the maintenance cost for equipments at offshore is more compared to that of onshore.

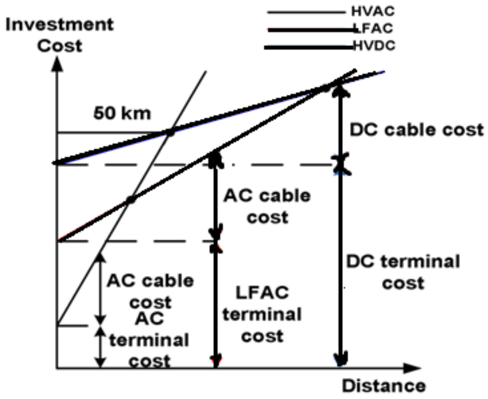
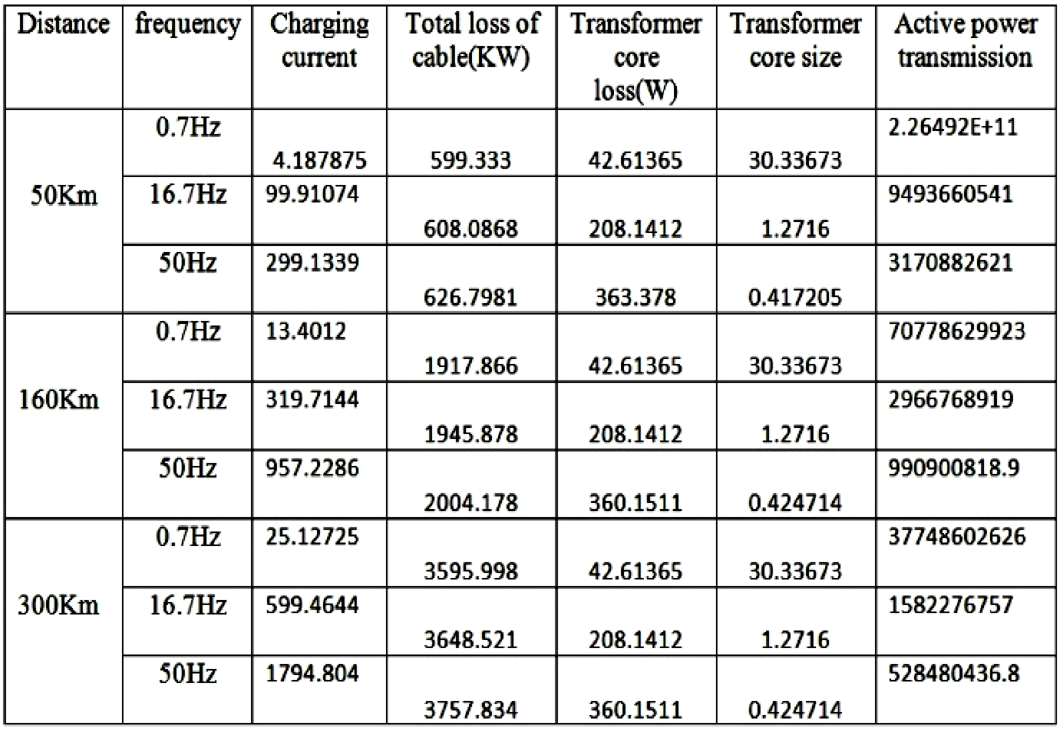


Fig. 2 Cost Comparison of Transmission systems

The cost comparison of different transmission systems are shown in Fig. (2). It is clear from the figure that the breakaway point increases in LFAC transmission system compared to conventional AC system. The investment cost is lower for the HVAC system than the HVDC, if transmission distance is shorter than 50Km. If the frequency is reduced, the slope of LFAC curve reduces, thereby making the LFAC much competitive when the distance between the offshore and onshore is in the range of 30 km to 150km.

The total losses of cable, core loss of transformer, charging current, transformer core size and power transmission have been calculated at different frequencies of 50 Hz, 16 Hz and 0.7 Hz and at a voltage of 132 kV and presented in Table 1. The analysis of the table clearly indicates that 0.7 Hz is the optimal frequency.

Table 1: Component losses Calculated values for different transmission distances.



Distance	frequency	Charging current	Total loss of cable(KW)	Transformer core loss(W)	Transformer core size	Active power transmission
50Km	0.7Hz	4.187875	599.333	42.61365	30.33673	2.26492E+11
	16.7Hz	99.91074	608.0868	208.1412	1.2716	9493660541
	50Hz	299.1339	626.7981	363.378	0.417205	3170882621
160Km	0.7Hz	13.4012	1917.866	42.61365	30.33673	70778629923
	16.7Hz	319.7144	1945.878	208.1412	1.2716	2966768919
	50Hz	957.2286	2004.178	360.1511	0.424714	990900818.9
300Km	0.7Hz	25.12725	3595.998	42.61365	30.33673	37748602626
	16.7Hz	599.4644	3648.521	208.1412	1.2716	1582276757
	50Hz	1794.804	3757.834	360.1511	0.424714	528480436.8

The graphs in Figs 3, 4 and 5 indicate the maximum possible power transmission at 0.7Hz, 16.7Hz, 50Hz frequencies for 50Km, 160Km, 300Km transmission line respectively. It is also shown that the power transmission gradually decreases with increase in transmission distance from 50 to 160 km but falls suddenly with large distance of 300 km. From the graphs, it is clear that power transmission is maximum for 0.7 Hz frequency compared to 16.7 Hz and 50 Hz.

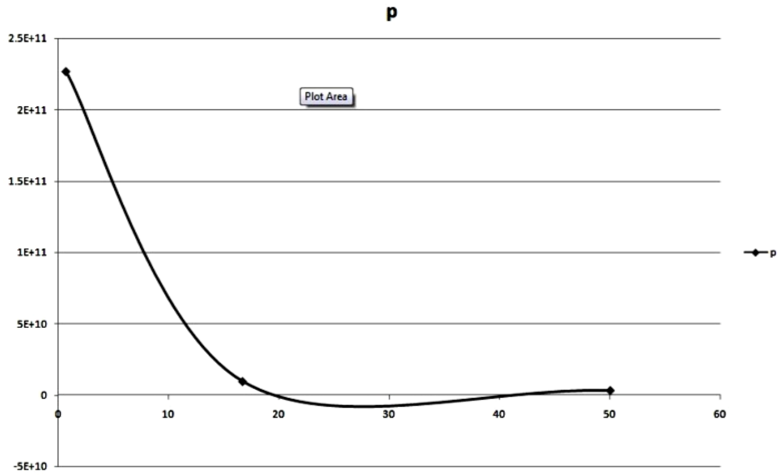


Fig. 3 Power transmission at 0.7hz, 16.7Hz, 50Hz frequencies for 50Km length cable

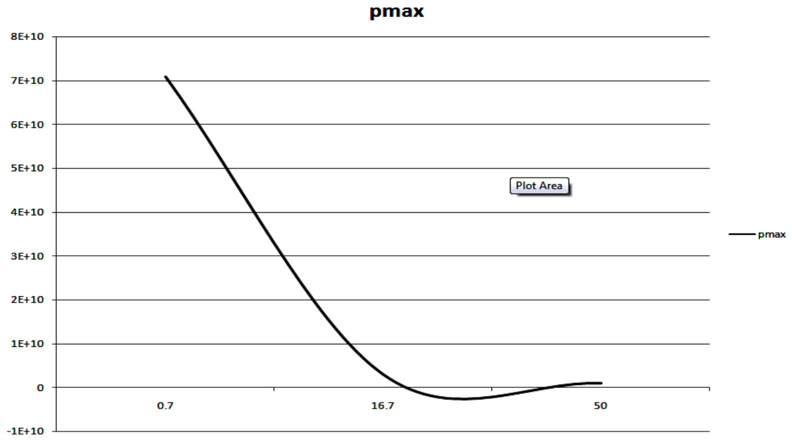


Fig. 4 Power transmission at 0.7hz, 16.7Hz,50Hz frequencies for 160Km length cable.

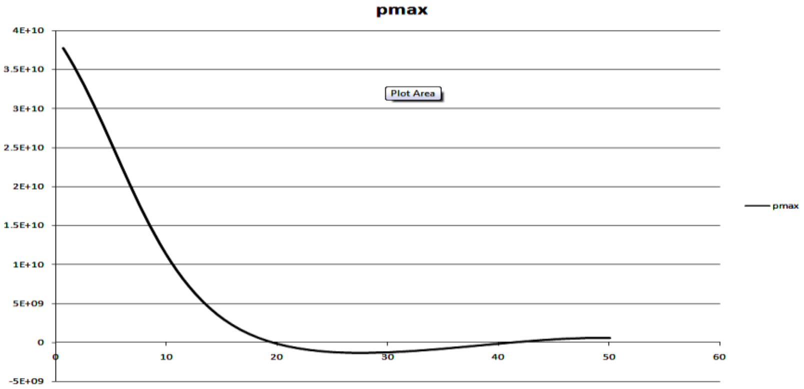


Fig. 5 Power transmission at 0.7hz, 16.7Hz,50Hz frequencies for 300Km length cable.

Figs 6, 7 and 8 show a comparison of losses at 0.7 Hz, 16.7 Hz, 50 Hz for 50 km, 160 km, 300 km transmission line respectively, wherein series-1, 2 and 3 indicate frequency, transformer core loss and transmission loss respectively. It is clear that core loss of transformer and total losses of transmission are less for 0.7 Hz compared to other two transmission systems.

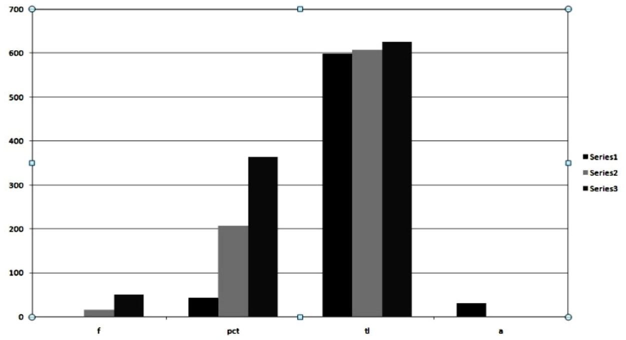


Fig. 6 Comparison of transmission loss and transformer core loss at 0.7Hz,16.7Hz and 50Hz for 50Km cable

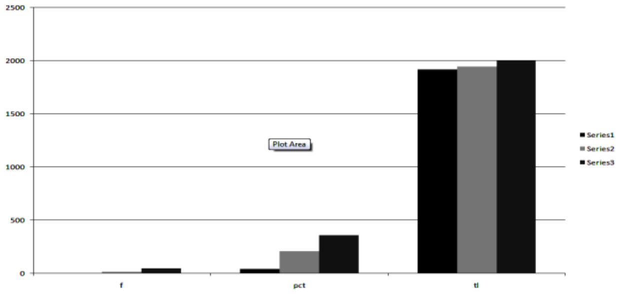


Fig7: Comparison of transmission loss and transformer core loss at 0.7Hz,16.7Hz and 50Hz for 160Km cable

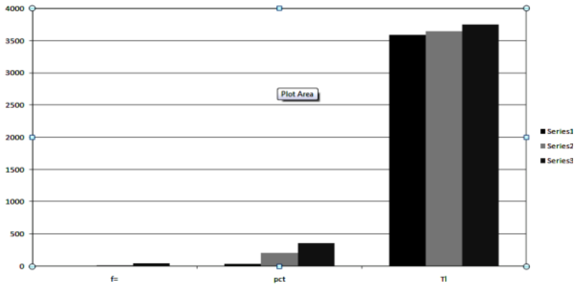


Fig. 8 Comparison of transmission loss and transformer core loss at 0.7Hz,16.7Hz and 50Hz for 300Km cable

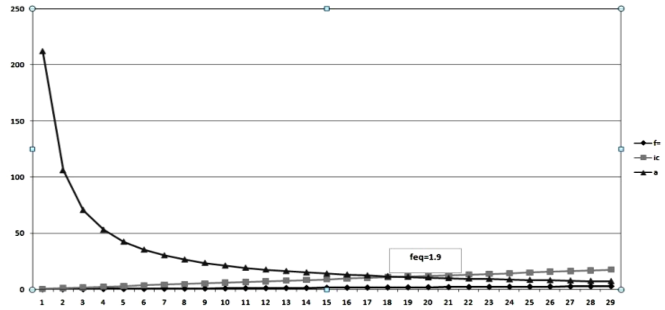


Fig. 9 Optimal frequency point for 50km submarine cable

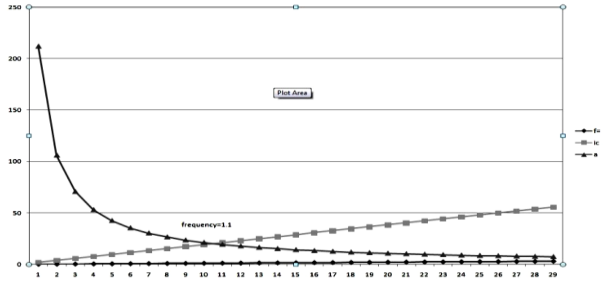


Fig. 10 Optimal frequency point for 160km submarine cable

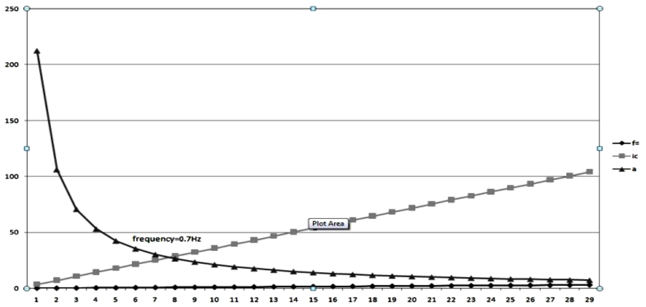


Fig. 11 Optimal frequency point for 300km submarine cable

Figs. 9, 10 and 11 show the point where charging current and area of the transformer intersect above which charging current increases and power transfer capability decreases. From the above three graphs, the low frequency 0.7 Hz is chosen as the optimal frequency.

VI. CONCLUSION

A LFAC transmission system with transmission frequency of 0.7 Hz as an alternative solution for conventional HVAC, HVDC and fraction frequency systems. Cyclo-converter converts the 50 Hz to the lower frequency. A suitable program is designed for loss calculation of various components at all frequencies from 0 to 50 Hz. Graphs have been drawn to show the comparison with conventional HVAC 50 Hz and fractional frequency 16.7 Hz and proposed frequency 0.7 Hz. A rough economic comparison with conventional HVAC and HVDC indicated that LFAC is competitive for short and intermediate distances range from 50 km to 170 km. It is shown that power transfer capability largely falls for long distances such as 300 km. The graphs and results show that LFAC system with 0.7Hz has transmission capability of cable is much greater than the conventional AC.

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