Improve the Voltage Profile in Transmission Lines by using Fractional Frequency Transmission System

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Abstract— This paper presents a low-frequency ac (LFAC) transmission system for 50/3HZ source. The LFAC system is interfaced with the main power grid with a voltage source inverter. The 50/3 supply voltage is connected to the load through the voltage source inverter. The LFAC system improves the transmission capacity and distance compared to the conventional AC solution at nominal frequency, e.g. 50HZ to 60HZ. And reduces the investment cost compared to the HVDC solution. In this project, comparative analysis is carried out for power transmission, for 1200km length at 50Hz and 50/3Hz. Test system of 765kV and 1200kV are selected as transmission voltage levels. Simulation is carried out on test system over Matlab simulink environment. Load at the receiving end is varied from 0% to 150% of Surge Impedance Loading (SIL) in steps of 25%. Also, computation has been carried out for sending & receiving end voltages, active power transfer capacity, reactive power transfer capacity, and compensation required for 1200km line. Results shows that for 50Hz test system of transmission line, power transfer is not possible without compensation, voltage profile and power transfer efficiency is out of the limit, but in FFTS, it is possible to transmit 5 to 6 times the rated power without any compensation and voltage profile and power transfer efficiency is within the limit.

Key words: DC Link, Filters, Power Transmission, Rectifier, Voltage Source Inverter

I. INTRODUCTION

A. *Over View of Power Transmission*

The natural resources for electricity generation in India are unevenly dispersed and concentrated in a few pockets. Hydro resources are located in the Himalayan foot hills and in the north-eastern region (NER). Coal reserves are concentrated in Jharkhand, Orissa, West Bengal, Chhattisgarh, parts of Madhya Pradesh, whereas lignite is located in Tamil Nadu and Gujarat. North Eastern Region, Sikkim and Bhutan have vast untapped hydro potential estimated to be about 35000 MW in NER, about 8000MW in Sikkim and about 15000 MW in Bhutan [1].

The distribution of energy resources and consumption centres are extremely unbalanced. The load centres are scattered at far-off places away from resource rich areas. Recent government initiatives for establishment of special economic zones have also given rise to new potential load centres. Projects are proposed to be located mostly at pit head/resource areas with each location having capacities in the range of 5,000-10,000 MW.

High Voltage DC (HVDC) and Ultra High Voltage DC (UHVDC) are suitable to transfer power over long distance at single point. Multipoint D.C power transmission is expensive and economical constraint limits its development. In recent years there has been great interest in the power industry in construction of Extra High Voltage AC (EHVAC) ac transmission lines. Many 500 kV and 760 kV transmission lines have been built across the world. Technical and economical limitations of E.H.V A.C transmission over long distance are overcome by reducing artificially series reactance and shunt susceptance of the line. It also increases the efficiency of power transmission and will reduce the temporary and transient over voltages.

B. *Present Transmission System of India:*

Electricity is a concurrent subject in India i.e., both the central and state governments are responsible for the development of the electricity sector. NTPC, NHPC, THDC, NEEPCO, SJVNL, NLC etc. are the central generation utilities and POWERGRID is the Central Transmission Utility [3]. At the State level, there are Generation and Transmission companies, Karnataka Power Transmission Corporation Ltd (KPTCL) in Karnataka. The country has been demarcated into five electrical Regions viz. Northern (NR),Eastern (ER), Western (WR), Southern(SR) and North Eastern (NER). However, NR,ER, WR and NER have been synchronously interconnected and operating as single grid – Central Grid (capacity about 110,000MW)[2]. Hitherto Southern region is asynchronously connected to the Central Grid through HVDC links. Now Southern grid is connected to National Electric Grid.

The national integration of grids has been achieved following the commissioning of the Raichur - Solapur 765 kV single circuit transmission line by the Power Grid Corporation of India Ltd (PGCIL). The development took place on December 31, nearly five months ahead of schedule in May. This line of 208 circuit kilometers (ckm) and 765-400 kV substations at Raichur and Sholapur, has been commissioned five months ahead of its contractual schedule. With this interconnection, the Indian power system has become one of the largest synchronous grids with about 232,000 MW of installed power generation capacity [3]. Thus Southern Grid has been synchronously connected to the rest of the Grid in the country. With this, the mission of ‘One Nation – One Grid – One Frequency’ has been successfully accomplished. The details of the existing transmission system in India are given in Table 1.1.

Transmission Lines	**As on March 2012** in circuit kilometers
HVDC+/- 500 kV	7478
765 Kv	7612
400 kV	125000
220 Kv	150000
Total-Transmission Lines	**293852**

Table 1.1 Existing Transmission System in India

C. High Density Transmission Corridor

In order to optimize ROW, high density transmission corridors (MW per meter) either by increasing voltage level or current order or both i.e. increase in voltage and current are need to be developed. Power intensity at different voltage level is tabulated in Table-1.2.

Voltage (kV)	220	400	765	1200
ROW meters (m)	35	46	64	90
Capacity (MW)	160-170	600-700	2500-3000	5000-7000
MW/m	5	15	45	90

Table 1.2 Power intensity in MW/meter at different voltage level.

It can be seen from Table 1.2 that power intensity at 220 kV and 400 kV corridors are 5 and 15 MW/m respectively, which is highly inefficient. With the increasing voltage, power intensity can be increased and transmission voltage up to 765kV level already operating. Thus it can be said that higher the transmission voltage, Voltage drop in line is reduced and power intensity/meter is greater as shown in Table 1.2.

D. Objective Of The Project

As adverted in section High Density Transmission Corridor, power intensity is greater as transmission voltage is increased and for 1200kV transmission system MW/meter is 90.Also higher the transmission voltage, lower the voltage drop. Voltage drop formula is given [6] as-

$$\triangle V = QX/ V^2 \qquad \text{-------} (1)$$

where $\triangle$ V is voltage drop
Q is the reactive power flow in transmission line
X is the line reactance
V^2 is the square of transmission voltage

Thus, the voltage drop is inversely proportional to the square of voltage and proportional to the reactance of the transmission line. Therefore, in order to raise transmission capability, we can either increase the voltage level or decrease the reactance of the transmission line. The reactance is proportional to power frequency, f ($X= 2\pi fL$). Hence, decreasing the electricity frequency (from 50 Hz to 50/3 Hz)can proportionally increase transmission capability. Thus, the objective of this project work is to compare the power transfer capability over 1200km, for 765kv at 50Hz and 50/3Hz for different surge impedance loading (SIL). Test system designed for 765kv transmission system for different SIL over matlab environment. Assessing the power transfer capability for EHVAC at 50Hz and 50/3Hz, a generator is designed to deliver this 765kV and not using a step-up transformer to achieve this voltage level. In this test system, transmission line is modeled for 1200km, as two 600km transmission line connected together. Load, along with active power load, inductive power load is added at the load side. Load is varied in steps of 25% from 0% to 150% of Surge Impedance Loading (SIL). Parameters to be noted for tabulation, as load is varied from 0% to 150% of SIL, in step of 25%, without compensation and with mid-point compensation, sending & receiving end, voltage, active power and power factor.

II. FRACTIONAL FREQUENCY TRANSMISSION SYSTEM

A. Overview

The AC power generated through various source is step-up to higher voltage, such as, 132kV, 220kv, 275kV, 345kV, 400kV, 500kV and 750kV [4] which are accepted as standard. Apart from these transmission voltages there exist two further voltage classes which have found use in the world but have not been accepted as standard. They are: 1000 kV (1050 kV maximum) and 1150 kV (1200 kV maximum)[5]. Higher the transmission voltage greater is the power intensity[5]. Not with standing, the fact that it helps reducing the voltage drop in transmission line and reduces the number of circuit kilometers. The voltage drop is inversely proportional to square of voltage and directly proportional to line reactance as shown in eq (1). As seen in eq (2) the line reactance of transmission line is directly proportional to transmission frequency, f. Thus by reducing the transmission frequency to 50/3Hz [6], and power being transferred with either EHVAC or UHVAC, the power intensity can be increased further.

FFTS to transfer power with 500kV as its transmission voltage over 1200km distance and comparing it with 50Hz transmission system; power transferred with FFTS is 2.5 times more that 50Hz system[7]. When power is transferred at 765kV, power transferred is 9000MW.

Currently, the application of FFTS is used in western countries to convert wind energy to electrical energy. Average wind speed in , Randolph, New Hampshire, United States of America (USA) is 35.1 mile/hour. Average offshore wind speed in USA is 26.5 mile/hour [8].

This projects objective is to review the power transfer ability with reduced frequency .i.e. 50/3Hz with transmission voltages being, 765kV and 1200kV for 1200km.

B. 765kv Transmission Line System

1) Methodology

Here the objective is to review the power transfer capability over a distance with FFTS. Thus, the required transmission voltage .i.e. 765kV maximum operating voltage is not obtained through step-up transformer rather its molded to generate this transmission voltage. The line parameter are used as shown in Table 2.1a

System voltage kV	750
Resistance in ohm/km	0.01220
Inductance in mH/km	0.89763
Capacitance in µ F/km	0.01285
Z (ohm)	264.2
SIL (MW)	2186.21

Table 2.1a Line parameter for 765kV transmission system.

Transferring power with 756kV as transmission voltage for 1200km. This distance is divided to two 600km connected together. Load is connected at the receiving end with operating voltage being 765V and frequency being 50Hz. The modeling ratio used is mentioned in Table 2.1b.

The frequency conversion carried in this project is AC-DC-AC CONVERTER with DC link. With appropriate LC filters output waveform can be viewed sinusoidal [7].

Voltage Ratio	1000:1 (765kV:765V)
Impedance Ratio	1:1
Power Ratio	(1000)2 /1= 10^6:1 (546MW:546W)

Table 2.1b Load modeling ratio for 765kV FFTS

Active power load is varied from 0% to 150% of SIL with 1000MVAR inductive load. Table 2.1c shows the 0% to 150% of SIL for 765kV FFTS

541 V	25%	50%	75%	100%	125%	150%
	546W	1.0931kW	1.6397kW	2.18621kW	2.7328kW	3.280kW

Table 2.1c SIL variation for 765kV FFTS

2) Frequency Converter To Synchronize With Grid Frequency

a) AC-DC-AC Converter

Voltage Source Inverter (VSI) with fixed DC link technique [10] used in designing inverter to convert 50/3Hz to grid frequency .i.e. 50Hz. Insulated-Gate Bipolar Transistor (IGBT) are used in inverter. Control of IGBT's is achieved Sinusoidal Pulse Width Modulator Technique.

b) Voltage Source Inverter With Fixed Dc Link

Fig 2.1 shows the typical power-circuit topologies of a three-phase voltage source inverter [10-11]. 'Edc' is the input dc supply and a large dc link capacitor (Cdc) is put across the supply terminals. Q1, Q2, Q3 etc. are fast and controllable switches. D1, D2, D3 etc. are fast recovery diodes connected in anti-parallel with the switches. 'A', 'B' and 'C' are output terminals of the inverter that get connected to the ac load.

A three-phase inverter has three load-phase terminals whereas a single-phase inverter has only one pair of load terminals. The current supplied by the dc bus to the inverter switches is referred as dc link current and has been shown as 'idc'. The magnitude of dc link current often changes in step as the inverter switches are turned on and off. The step change in instantaneous dc link current occurs even if the ac load at the inverter output is drawing steady power. However, average magnitude of the dc link current remains positive if net power-flow is from dc bus to ac load. The supply line impedance, if not bypassed by a sufficiently large dc link capacitor, may cause considerable voltage spike at the dc bus during inverter operation. This may result in deterioration of output voltage quality, it may also cause malfunction of the inverter switches as the bus voltage appears across the non-conducting switches of the inverter. Also, in the absence of dc link capacitor, the series inductance of the supply line will prevent quick build up or fall of current through it and the circuit behaves differently from the ideal VSI where the dc voltage supply is supposed to allow rise and fall in current as per the demand of the inverter circuit.

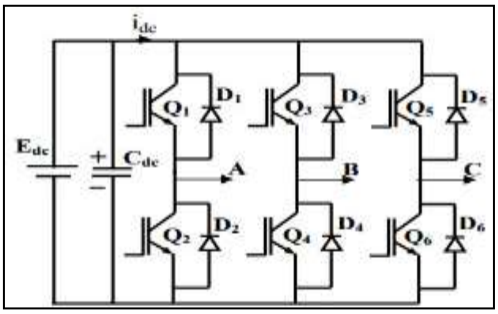

Fig 2.1 Basic Six pulse Three phase inverter.

The two switches of an inverter-leg are controlled in a complementary manner. When the upper switch of any leg is 'on', the corresponding lower switch remains 'off' and vice-versa. When a switch is 'on' its emitter and collector terminals are virtually shorted. Thus with upper switch 'on', the emitter of the upper switch is at positive dc bus potential. Similarly with lower switch 'on', the emitter of upper switch of that leg is virtually at the negative dc bus potential. Emitters of all the lower switches are solidly connected to the negative line of the dc bus.

c) DC Link

The DC link capacitor helps to keep the large transients (generated from the switching frequency) from radiating back to the input. This can also help prevent the switching network from oscillating or triggering inadvertently at an inappropriate moment and causing a short.

d) Inverter Technique

Technique used here is Sinusoidal Pulse Width Modulator Technique (SPWM)[10], [13]. The voltage source inverter that use PWM switching techniques have a DC input voltage (VDC = Vg) that is usually constant in magnitude. The inverter takes this DC input and to give AC output, where the magnitude and frequency can be controlled. There are several techniques of Pulse Width Modulation (PWM).The efficiency parameters of an inverter such as switching losses and harmonic reduction are principally depended on the modulation strategies used to control the inverter. In this design the Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions.

SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal. Generally, three sinusoidal waves are used for three phase inverter Fig 2.2 shown the matlab model for generating gate pulses. The sinusoidal waves are called reference signal and they have 120 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches. In order to avoid undefined switching states and undefined AC output line voltages in the VSI, the switches of any leg in the inverter cannot be switched off simultaneously. The phase outputs are mutually phase shifted by 120 angles. Rectification - Inversion circuit used is shown in Fig 2.3 Control block is masked to provide inputs for gate pulse generation as shown in Fig 2.4 Fig 2.5 shows the IGBT block value.

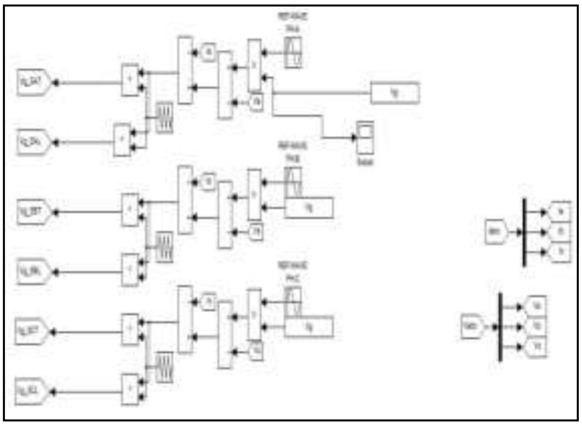

Fig 2.2 Gate pulse generation for Inverter (IGBT)

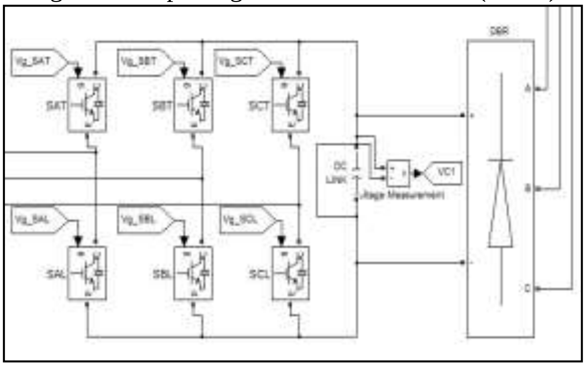

Fig 2.3 Rectification-Inversion Circuit

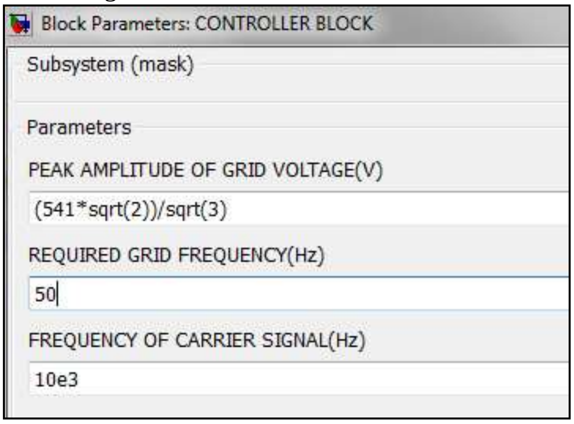

Fig 2.4 Masked Control Block

Fig 2.5 IGBT Block Value

e) Filter

Output of the inverter is "chopped AC voltage with zero DC component". It contain harmonics, an LC section low-pass filter [10] is normally fitted at the inverter output to reduce the high frequency harmonics as shown in Fig 2.2.2.3 -

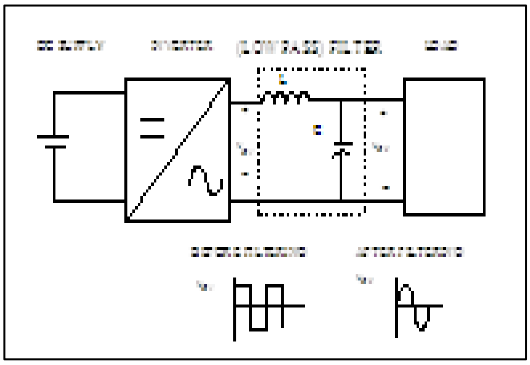

Fig 2.6 Basic Filter Circuit and output waveform

f) Three Phase Load

Three phase load in operated as modeling ratios.
Voltage Ratio = 1000:1 (765kV:765V)
Impedance Ratio = 1:1
Power Ratio = (1000)2 /1= 10^6:1 (546MW:546W)

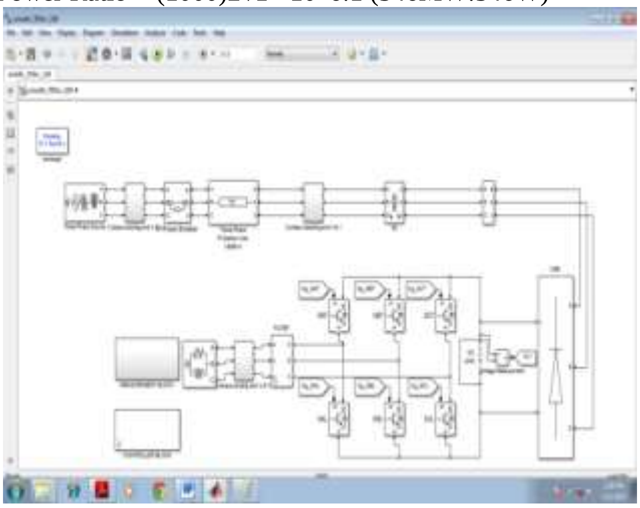

Fig 2.7indirect method transmission system

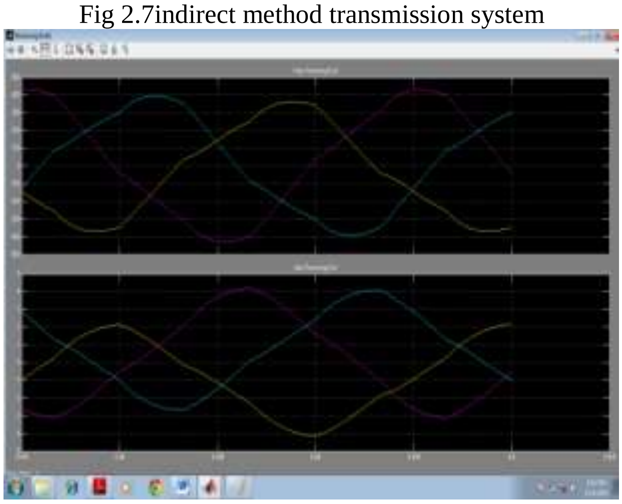

Fig 2.8 output voltage &current of the indirect method

III. SIMULATION RESULTS OF 765KV AND 1200 KV FFTS

Thus source voltage is set to 541 kV and 848.5kV load is modeled at operate at 1000:1 ratio .i.e. 541V and 848.5V by varying the active power demand with constant inductive load, 1kvar (which is equal to 1000MAVR in 50Hz system; 10^6:1) and tabulating the voltage, current, power factor, Active power at sending and receiving end in Table 3.1 and 3.2 respectively.

$SIL_{(MW)}$	$V_{s(kV)}$	$I_{s(A)}$	Pf_S	$P_{S(MW)}$	$V_{R(V)}$	$I_{R(A)}$	pf_R	$P_{R(MW)}$
546.6	572	1000	0.9879	979	440	1700	0.72	933
1093.1	572	1000	0.9879	979	440	2250	0.85	1458
1639.7	572	1000	0.9879	979	440	2450	1	1867
2186.21	572	1000	0.9879	979	440	2900	1	2210
2732.8	572	985	0.9879	964	438	4340	0.98	3226
3280	572	982.3	0.9879	961	424	4600	0.98	3310.6

Table 3.1 Measuring parameter for 765kV FFTS

$SIL_{(MW)}$	$V_{s(kV)}$	$I_{s(A)}$	pf_S	$P_{S(MW)}$	$V_{LR(V)}$	$I_{LR(A)}$	pf_R	$P_{R(MW)}$
1333.3	840	1108	0.9877	1592	691	1610	0.9	1734
2666.6	840	1097.4	0.9877	1577	690	3600	0.9	3872
4000	840	1110.6	0.9877	1596	690	4000	1	4787.4
5333	840	1140	0.9877	1638	690	6100	0.9	6561
6666.3	840.7	1140	0.9877	1640	687	6360	0.9	6811
8000	840	1146	0.9877	1647	685	7650	0.9	8169

Table 3.2 Measuring parameter for 1200kV FFTS

Vs(kV) is sending end voltage in kilo volts, Is(A) is sending end current in amps, pfs is the power factor at sending end, Ps(MW) is the active power at sending end, VR(kV) is receiving end voltage in kilo volts, IR(A) is receiving end current in amps, pfR is the power factor at receiving end, PR(MW) is the active power at receiving end. Thus by varying the load from 0% to 150% of SIL parameters to be noted are, sending and receiving end, voltage, Active power and power factor which are tabulate for critical review.

IV. POWER TRANSFER AT 50HZ

A. *Overview*

The power is transmitted for a distance of 1200km by cascading two 600km transmission lines. The transmission frequency being 765kV and 1200kV but the frequency here is conventional 50Hz. The parameter like, sending and receiving end voltage, active power and power factors are calculated for different SIL without compensation and with compensation. Obtained values are tabulate and reviewed critically.

B. *765kv and 1200Kv Transmission System*

The methodology is similar to FFTS, where the transmission voltage is generated and not using a step-up transformer to achieve this voltage level. The parameter like, sending and receiving end voltage, active power and power factors are calculated for different SIL without compensation and with compensation. Obtained values are tabulate and reviewed critically. To prevents excessive voltage variations in a power system, the ratio of the magnitude of the receiving end voltage to the magnitude of the ending end voltage is generally within

$$0.95 \leq VS/VR \leq 1.05$$

765kV phase to phase voltage limits are 728.5kV to 805kV

442 kV Phase to neutral voltage limits are 420kV to 465kV

Three phase load is been varied from 0% to 150% SIL. The details of load variations are tabulated below in Table 4.1

541kv	25%	50%	75%	100%	125%	150%
	546.6MW	1093.1MW	1639.7MW	2186.21MW	2732.8MW	3280MW

Table 4.1 SIL varied from 0% to 150%

Similarly for 1200kV transmission line system

1200kV phase to phase voltage limits are 1143 kV to 1263 kV

693kV Phase to neutral voltage limits are 660 kV to 730 kV

Three phase load is been varied from 0% to 150% SIL. The details of load variations are tabulated below in Table 4.2

848.5kv	25%	50%	75%	100%	125%	150%
	1333.3MW	2666.6MW	4000MW	5333MW	6666.3Mw	8000MW

Table 4.2 SIL varied from 0% to 150%

V. RESULT & DISCUSSION

Considering 100% of SIL for both transmission voltages and reviewing critically. Table 5.1 shows the parameter parameters for 765kV transmission system without and with compensation and Table 5.2 shows the measured parameters for 1200kV transmission system without and with compensation for 50Hz transmission system respectively. Table 5.3 and 5.4 shows the measured parameter for 765kV 1200kV transmission system for 50/3Hz without compensation respectively.

$SIL_{(MW)}$ 2186.21								
Compensation	$V_{s(kV)}$	$I_{s(A)}$	pf_S	$P_{S(MW)}$	$V_{R(kV)}$	$I_{R(A)}$	pf_R	$P_{R(MW)}$
Without	416	664	0.9	431	186	1525	0.9	442.2
With	425	3320	0.83	2028	427	3076	0.9	2047

Table 5.1 765kv Systems Measured Parameters For 50Hz Transmission Frequency

$SIL_{(MW)}$ 5333								
Compensation	$V_{s(kV)}$	$I_{s(A)}$	pf_S	$P_{S(MW)}$	$V_{R(kV)}$	$I_{R(A)}$	pf_R	$P_{R(MW)}$
Without	580	1380	0.86	1193	302.5	2280	0.98	1171
With	705	5320	0.83	5391	690	5000	0.97	5378

Table 5.2 1200kv Systems Measured Parameters For 50Hz Transmission Frequency

From Table 5.1 it can be observed, voltage at sending end is below 5% tolerance which is between 0.95% to 1.05% i.e. Phase to neutral voltage limits being 420kV to 465kV. The power at sending and receiving end is 431MW & 442.2MW respectively for 100% SIL. Thus it can said that the voltage profile and active power are not within acceptable range and the test system in unstable. Now, by adding mid-point capacitance of 414 MVAR, sending and receiving end voltages are well within limits, also the power transferred is as per the load demand.

Thus, asserting, the voltage profile ratio which is receiving end divided by sending end (Vr/Vs) is 1.004, well within its limit. Also, Power transfer efficiency is given as Receiving end power by sending end power (Pr/Ps) in percentage is 99%.

Thus, asserting, the voltage profile ratio which is receiving end divided by sending end (Vr/Vs) is 0.98, well within its limit. Also, Power transfer efficiency is given as

Receiving end power by sending end power (Pr/Ps) in percentage is 99%.

From Table 5.2 it can be observed, voltage at sending end is below 5% tolerance which is between 0.95% to 1.05% .i.e. Phase to neutral voltage limits being 660 kV to 730 kV. The power at sending and receiving end is 1193 Mw and 1171 MW respectively for 100% SIL. Thus it can be said that the voltage profile and active power are not within acceptable range and the test ssystem in unstable. Now, by adding mid-point capacitance of 1344 MVAR, sending and receiving end voltages and active power are as required.

Thus, asserting, the voltage profile ratio which is receiving end divided by sending end (Vr/Vs) is 0.98, well within its limit. Also, Power transfer efficiency is given as Receiving end power by sending end power (Pr/Ps) in percentage is 99%.

Thus the mid-point compensation required for 765kV transmission system is 414MVAR and for 1200kV transmission system is 1344MVAR which is 3.2 times of 765kV transmission system. Notwithstanding, the fact that the MVAR required for 1200kV transmission system is 3.2 times more 765kV system but the power transferred is 2.5 times of 765kV system.

$SIL_{(MW)}$	$V_{s(kV)}$	$I_{s(A)}$	pf_s	$P_{s(MW)}$	$V_{R(V)}$	$I_{R(A)}$	pf_R	$P_{R(MW)}$
2186.21	572	1000	0.9879	979	440	2900	1	2210

Table 5.3 765kV Systems Measured Parameters For 50/3 Hz Transmission Frequency

As seen from Table 5.3, it can be said that the receiving end voltage profile is well within limits of 5% tolerance band while sending end is not. By adding a positive MVAR, this voltage can be set within its tolerance band. The power transferred is satisfactory for 100% SIL. Similarly for 1200kV transmission line system

$SIL_{(MW)}$	$V_{s(kV)}$	$I_{s(A)}$	pf_s	$P_{s(MW)}$	$V_{LR(V)}$	$I_{LR(A)}$	pf_R	$P_{R(MW)}$
5333	840	1140	0.98	1638	690	6100	0.97	6561

Table 5.4 1200kV Systems Measured Parameters For 50/3 Hz Transmission Frequency

Thus, comparing for EHVAC transmission system, it can be asserted, for 50Hz transmission system with compensation of 414MVAR at mid-point, the required voltage and power ratings limits are achieved. Not with standing, for 50/3 Hz transmission system, the voltage, current and active power limits are achieved. Thus without compensating in 50Hz transmission system power that is transferred is around 442.2 MW and without compensation in 50/3HZ transmission system power transferred is 2210MW which is 5 times greater than conventional system. However, one should note that in 50/3Hz transmission system, the current caring over conductance is low to 50Hz transmission system, also the power factor is better in 50/3Hz system.

VI. CONCLUSION

The 50Hz transmission system of voltage 765kV and 1200kV at a distance of 1200km is studied in this project. The receiving end and sending end voltage, active power and power factor are not within the limit. So the test system is unstable. For test system with mid-point series compensation, the receiving end and sending end voltage, active power and power factor are within limits. Decreasing the line reactance by reduced frequency to 50/3Hz. The test system with fractional frequency transmission system, the power transferred is 5 to 6 times the rated power. In FFTS the receiving end voltage and power factor are within limits.

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