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HIGH FREQUENCY POWER CABLE MODELING FOR SCREEN VOLTAGE CALCULATION OF DIFFERENT CABLE LENGTH WITH INDUCTION MOTOR DRIVE SYSTEM (VFD)

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ABSTRACT

This paper discussed on high frequency power cable modeling, simulation and analysis of the cable parameters variation. Also the variation of screen voltage, cable input and output phase voltage is discussed in the new developed power cable model. In this research paper, the input and output cable screen voltage are measured. The phase voltage for the different range of series inductance and shunt capacitance due affects the increasing cable length. The power cable parameters are accurately calculated for the cable connected between Variable Frequency Drive (VFD) and Induction Motor. An improved new high-frequency cable model is developed to represent the behaviors of cables connected between drive (VFD) and the motor terminal. The cable parameters and cable behavior is studied by mathematical functions in frequency domain. For different range of cable length are accounted in the new power cable equivalent circuit are developed and the same has been implemented and the results are presented in MATLAB/SIMULINK.

Keywords: power cable modeling, variable frequency drive, cable parameter, screen voltage, induction motor drives.

INTRODUCTION

The variable frequency drives (VFD) of induction motors drive system which runs with long power cable in the modern industrial application. The induction motor (VFD) drive uses pulse width modulation (PWM) technique which is responsible for transients reflected overvoltage and high switching transient current affects the common mode voltage. As a result it leads to several serious problems occur and electromagnetic interference (EMI). The Induction motor drives are used in industrial application including high efficiency, precise control of the induction motor speed and holding of the motor torque at very low speed. On the other hand these systems require a long motor lead that is why the motors often experience overshoot voltage stress due to the reflected wave. These reflected over shoot voltage increases with the cable and new mathematical equation are developed in frequency domain and describing the transient voltage and current [1]. The transient over voltage is determined by reflection coefficient and same is tied to the impedance mismatch between the cable and the motor end terminal. [2] [3]. The suitable filter was designed and connects the induction motor terminal and clamps the motor terminal reflected voltage at a safer level. The voltage pulses at the motor terminal to improve the voltage distribution of between inter coil and inter turn in the induction motor and also recover the additional energy gained from the motor and suppressing the overshoot voltage due to the long power line effect and back to the VFD systemare studied [4] [5]. An accurate frequency-dependent cable model is developed using a higher-order multiple sections, which includes the skin effects as well as dielectric losses. The model parameters are identified based on the measured DM impedance characteristics in a different wide frequency range from hundred Hz to ten MHz. Then, an improved motor model is proposed which accurately captures the high switching frequency DM and CM impedance characteristics from hundreds of HZ to tens of MHZ the proposed methodology is verified experimentally as well as compared against two conventional models. It is shown that the proposed model represents an appreciable improvement in predicting the motor over voltage transients [6] for many of these reasons the development of accurate high frequency cable simulation models is crucial for an appropriate analysis of overvoltage and EMI in lower drive systems. Several contributions based on lumped parameters schematization of the cables and the selection of lumped elements for coupled lossy transmission lines which is used to develop a high frequency model of the cable in a PWM drive. It has been presented in technical literature [6]-[7]. In [8] [9], the conducted electromagnetic emissions in induction motor drive systems are well discussed in time domain as well as frequency domain analysis. The paper [10] [11] are discussed about high frequency cable modeling accounting different cable parameters and practical results are discussed. The sheath loss factor and energy loss in the middle of the cable at the flat touching arrangement are studied in detail [12]. Several characteristics of cables, the effects of sheath circulating current and the relationship between the sheath permissible current are analyzed in the paper [13].The reflected overshoot voltage are increasing the cable length as well cable parameter are analyzed in this research paper [14].The single core cable circulating

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current are estimated with effect of cable parameter variation and Cable sheath loss factor are studied in the paper[15] [16] But none of the above papers focused the cable modeling covering screen voltages variation with cable length for the power cables. The research paper describes the effect of shunt capacitance and series inductance variation is independent with the cable length. The MATLAB simulation modeling is implemented in the new power cable model and measured the voltage and current in both input and output end. The modeling was done for both cable parameters and screen parameters and same are connected between VFD and motor to check the effectiveness of the new power cable model.

THE PROPOSED SYSTEM MODEL

The presented method is completely based on the important parameters of the power cables connected between VFD and Induction motor. The mathematical model for power cables including phase conductors and screens developed using MATLAB/Simulink The proposed concept in this paper is based on mathematical approach to formulate the cable equations and the same are developed. Also the developed models are integrated with VFD fed Induction motor. In this approach, predicted the self impedance of sheath (Z_{self}), mutual impedance of the sheath ($Z_{s\text{-}mutual}$), mutual impedance between the sheath and same conductor (Zaa), mutual impedance between the sheath and another conductor (Z_{ab}), the self impedance of phase conductor, self impedance of the screen, mutual impedance of the phase and screen, mutual impedance between phase conductor and capacitance between phase and screen are considered in the proposed model.

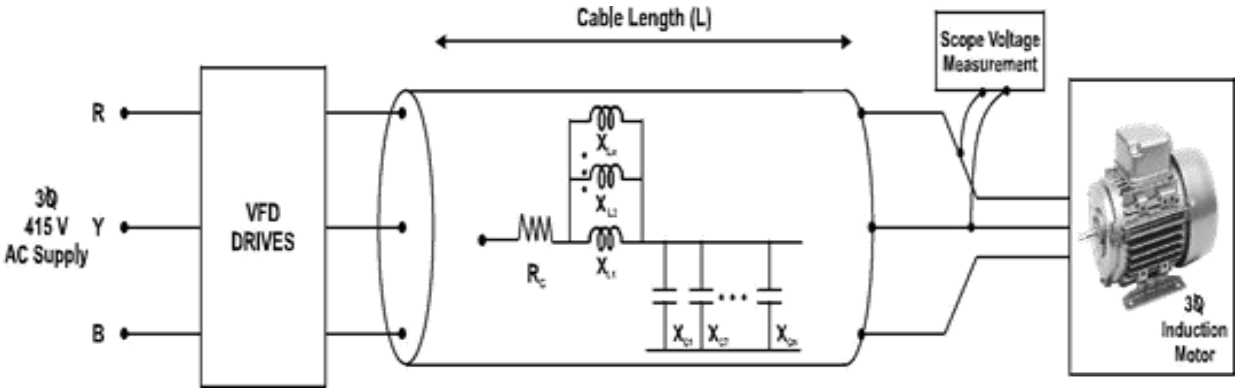

Figure-1. Power cable model VFD drive with three phase induction motor.

POWER CABLE PARAMETER CALCULATION

Cable capacitance calculation

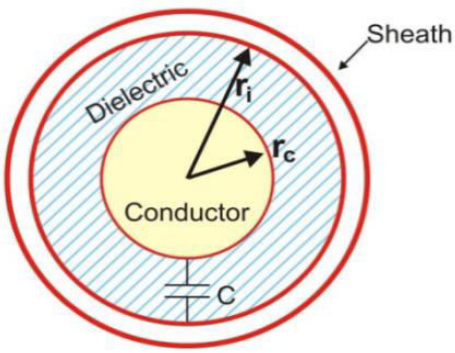

Figure-2. Single core cable.

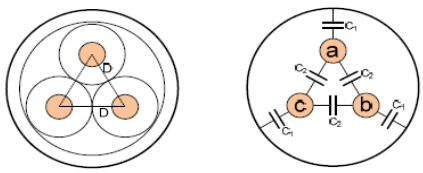

Figure-3. Three core cable.

The capacitance between conductor to conductor and conductor to sheath are calculated in the three core power cable as follows. Where C_{cs} = Capacitance between conductors to conductor, C_{cc} = Capacitance between conductors to sheath. The potential of the star point terminal nearly equal to zero. The equivalent capacitance between the star point and core

$$C_{CN} = 3C_{cc} \tag{1}$$

The capacitance of the each conductor to neutral

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$$C_N = C_{CS} + 3C_{cc} \quad (1)\, C_{CC} = \frac{C_B}{2} - \frac{C_A}{6} \tag{2}$$

$$C_N = \frac{C_A}{3} + 3\left(\frac{C_B}{2} - \frac{C_A}{6}\right) = 3\frac{C_B}{2} - \frac{C_A}{6} \tag{3}$$

The capacitance between conductor 1, 2, and 3rd conductor to sheath are calculated as follow (4)

$$= C_{CC} + \frac{C_{CC}}{2} + \frac{C_{CS}}{2}$$
$$= \frac{3C_{CC}}{2} + \frac{C_{CC}}{2} = \frac{1}{2}\left(3C_{CC} + C_{CS}\right) \tag{4}$$

Cable impedance calculation

(i) Mutual impedance among sheath and same conductor

$$Z_{aa} = 0.000989F_s + j0.0029F_s L_m \frac{D_e}{r}\Omega/km \tag{5}$$

(ii) Mutual impedance among sheath and another conductor

$$Z_{ab} = 0.000989F_s + j0.0029F_s L_n \frac{D_e}{d}\Omega/km \tag{6}$$

(iii)Self impedance of the sheath

$$Z_{self} = R_{ac} + 0.000989F_s + 0.0029F_s l_n \frac{D_e}{d}\Omega/km \tag{7}$$

(iv) Mutual impedance of the sheath

$$Z_{mutual} = 0.000989F_s + j0.0029F_s l_n \frac{D_e}{d}\Omega/km \tag{8}$$

F_s = Input supply frequency

D_e = Earth return path equivalent

r = Sheath radius

d = Spacing between center of the conductor

R_{ac} = AC sheath resistance Ω/km

Z_{sp} = Self-impedance of the phase conductor

$$Z_{sp} = R_{dc} + R_{er} + jk_{ff}\log\left[\frac{D_{er}}{GMR_{pc}}\right]\Omega/km \tag{9}$$

Z_{ss} is the self-impedance of screen conductor

$$Z_{ss} = R_x + R_e + jK_{ff}\log\left(\frac{D_{er}}{GMR_x}\right)\Omega/km \tag{10}$$

Z_{ps} is the mutual impedance between the phase and screen conductor

$$Z_{ps} = R_{er} + jk_{ff}\log\left(\frac{D_{er}}{D_n}\right)(\Omega/km) \tag{11}$$

Z_{xx} is the mutual impedance between the phase conductors

$$Z_{xx} = R_{er} + jk_{ff}\log\left(\frac{D_{er}}{GMD}\right)\Omega/km \tag{12}$$

C_{ps} is the capacitance between phase and screen

$$C_{ps} = 0.024147\left[\frac{\varepsilon_{rpsi}}{\log\left(\frac{D_{psi}}{d_{psi}}\right)}\right]\mu f/km \tag{13}$$

Where

Z_{sp} = Self-impedance of the phase conductor

R_{DC} = dc resistance of the phase conductor,

R_{er} = Resistance of the earth return path,

K_{ff} = Frequency factor

GMR_{pc} = Geometric mean radius of phase conductor,

r radius of the conductor

μ_r = Relative permittivity of the conducting material

D_{er} = Distance to equivalent earth return path,

f nominal frequency of the cable,

d = Diameter of the one strand in meter

Z_{ss} = Self-impedance of screen conductor.

R_x = dc resistance of the phase screen conductor

GMR_x = Geometric mean radius of phase screen insulator

ρ = Resistivity of the conductor,

r_{ext} = External radius of phase and screen insulator,

r_{int} = Internal radius of the phase and screen insulator

Z_{ps} = Mutual impedance between the phase and screen conductor

D_n = Distance between the phase conductor and Mean radius at phase screen insulator

Z_{xx} = Mutual impedance between the phase conductors,

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n = Total number the conductor
C_{ps} = Capacitance between phase and screen
ε_{rpsi} = Relative permittivity of the phase and screen insulator
D_{psi} = External diameter of phase and screen insulator
d_{psi} = Internal diameter of outer screen insulator
ρ_{cu} = Resistivity of phase conductors
N = Number of strands in the phase

Cable sheath current calculation

The ac current flow in the single conductor cable, the ac voltage induced between the sheath and cable conductor that effects magnetic coupling in the power cable. The sheaths of the cable are bounded at their end increasing the eddy current and occur additional loss I^2R in the sheath are accounted by increasing the conductor resistance. Single conductor cable with bonded sheath and operating three phases are arranged equilateral triangular formation and increasing the conductor resistance are calculated [25] as follows:

$$\Delta R = r_S\left(\frac{x_m^2}{r_s^2 + x_m^2}\right) \quad (14)$$

$$r_s = \frac{0.2}{(r_o + r_i)(r_o - r_i)} \quad (15)$$

x_m = Mutual reactance between conductor and sheath in ohm
r_s = Per phase sheath resistance in ohm
the mutual inductive reactance between cable sheath and conductor are calculated from the following equation

$$x_{xm} = 0.2794 \log_{10} \frac{2d}{r_o + r_i} \quad (16)$$

$GMR = D_s - \sqrt{r_o + r_i}$
GMD =Dm= d

In other hand, the mutual inductance between sheath and conductor are derived from the below equation

$$x_m = 0.2794 log_{10} \frac{D_m}{D_S} = 0.1213\ ln \frac{D_m}{D_s} \quad (17)$$

The single conductor cable, sheath current including positive and negative sequence current flow, the total resistance R_t

$$R_t = r_c + \frac{r_s x_m^2}{r_s^2 + x_m^2} \text{Ohm/km/phase} \quad (18)$$

R_t = Total positive or negative sequence resistance with sheath current effect

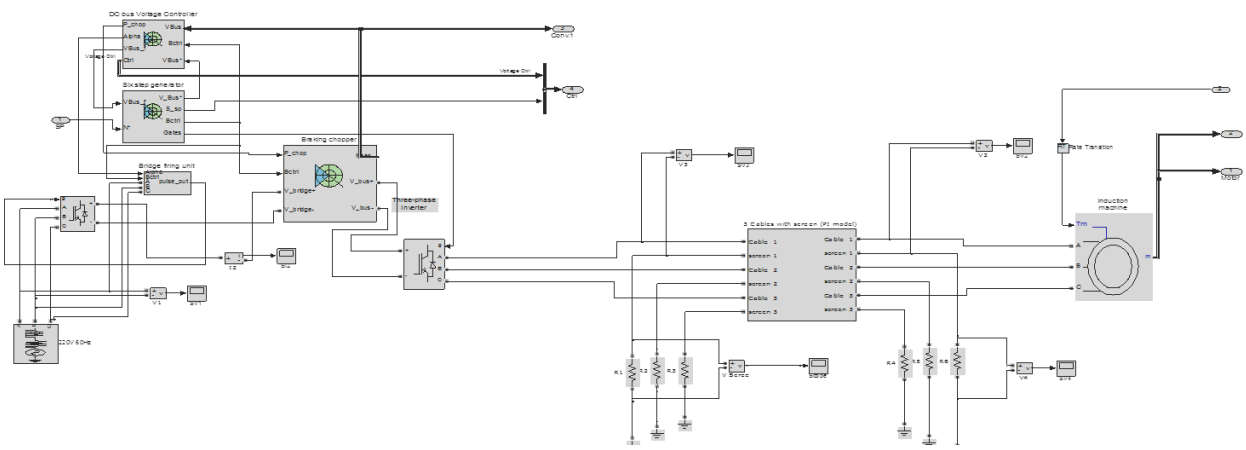

Figure-4. Matlab simulink model.

r_c= ac resistance of the cable conductor including skin effect

The cable sheath loss are calculated due to the effect of cable sheath current

$P_{SHEATHLOSS} = I^2 \Delta R$
ΔR = Increasing resistance in ohm
I^2 = Current in the one conductor in amps

r_s = Sheath resistance per phase in ohm/km
for the three round conductor cable for increase the conductor resistance due the sheath current effect are calculated [24] as follows:

$$\Delta R_{three-r} = 04416 \frac{s^2}{r_s(r_o + r_i)^2} \text{ohm/km/phase} \quad (19)$$

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S is the distance between sheath middle and conductor middle for three conductors in round formation

$$S = \frac{d+2T}{\sqrt{3}} \quad (20)$$

r_o= Outer radius of the lead sheath cable in cm
r_i = Inner radius of the lead sheath cable in cm
S = Distance between sheath middleto conductor middle in cm
d = Conductor diameter in meter in cm
T = Insulation thickness of the conductor in cm

The sheath can be short-circuited, bonded and grounded the sheath induced voltage decrease to zero but sheath current flow is along the sheath.

MATLAB SIMULINK MODEL DESCRIPTION

Typical Figure-4 Simulink model consists of Power input section, six step inverter section, DC Bus voltage controller, Power cable model and Induction motor model. The Drive includes bridge rectifier, DC link section, Inverter section and Brake chopper wherein input voltage fed to the bridge rectifier is3 phase, 415V 50 Hz supply. It converts the 3 phase AC into DC the DC link voltage is 580 volts. Also it contains brake chopper which is used for braking during regeneration of the machine. Figure-5 shows the inductance and capacitance coupling model is connected each phase and screen circuits. Figure-6 shows the PI model cable circuits in this proposed model, simulation have the following parameters.

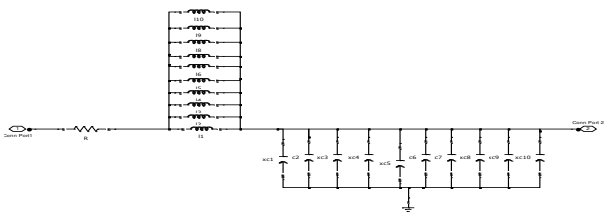

Figure-5. Series Inductance and shunt capacitance Single core model.

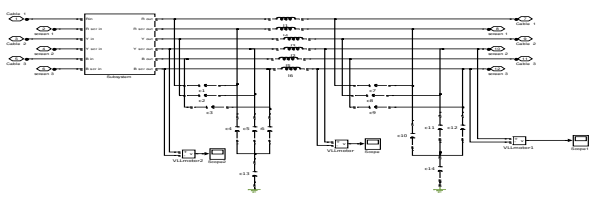

Figure-6. Three phase pi model cable.

Table-1. Cable parameter: Three core cable

Series inductance (L)	0.397MH/KM
shunt capacitance (Cp)	0.761µf/KM
DC resistance RDC	0.2680Ω/KM
AC resistance RAC	0.3420Ω/KM
Reactance XL	0.11Ω/KM
Impedance Z	0.359Ω/KM
Screen with ground resistance	15Ω

Table-2. Motor configuration: Squirrel cage motor.

Nominal power	5 HP
Nominal (Line-Line) voltage	565V
Frequency	50Hz
Stator resistance	1.115Ω
Rotor resistance	1.083Ω
Stator inductance	5.974mH
Rotor inductance	5.974mH
Mutual inductance	0.2037H

RESULTS AND DISCUSSIONS

Case 1: Cable length 250 meter

The proposed model has been simulated for 250 meter length of the cable and results are shown below. Figure-7 shows the Screen Input and output voltage Figure-8 shows the Screen output voltage. Figure-9 shows the cable input and output voltage.

Case 2: Cable length 500 meter

The proposed model has been simulated for 500meter length of the cable and results are shown below. Figure-0 shows the Screen Input output voltage. Figure-11 shows the Screen output voltage, Figure-12 shows the cable input output voltage.

Case 3: Cable length 750 meter

The proposed model has been simulated for 750meter length of the cable and results are shown below. Figure-13 the Screen Input output voltage. Figure-14 shows the Screen output voltage, Figure-15 shows the cable input output voltage

Case 4: Cable length1000 meter

The proposed model has been simulated for 1000meter length of the cable and results are shown below. Figure-16 the Screen Input output voltage. Figure-17 shows the Screen input voltage, Figure-18 shows the

screen output voltage and Figure-19 cable end input and output voltage

It's interesting to note that the screen voltage is increasing with varying the cable length. The PI section which is generated screen voltage by the change in flux linkage due to high switching frequency. The above results are compared with different cable length. The cable output voltage increased nearly double the dc link voltage the Table-1 (cable data for 1km) and Table-2 (Induction motor parameter) are consider for the Matlab simulation model

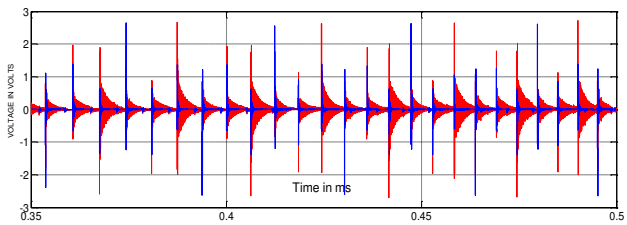

Figure-7. Cable screen input and output voltage (250 meter).

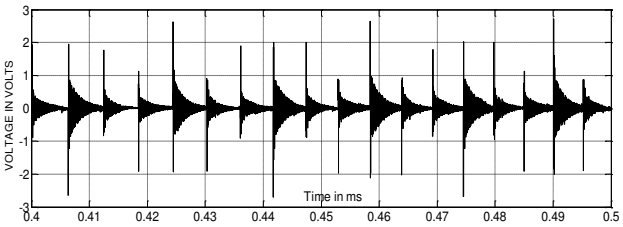

Figure-8. Cable screen output voltage (250 meter).

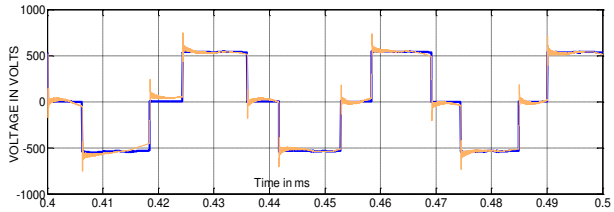

Figure-9. Cable end input and output voltage (Line-Line-250 meter).

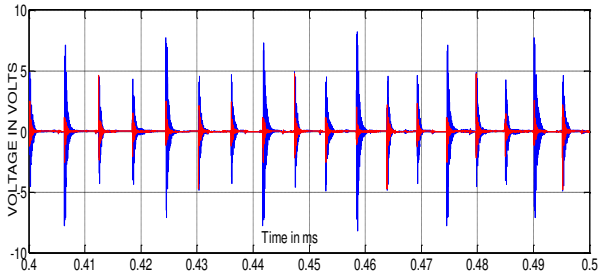

Figure-10. Cable screen input and output voltage (500 meter).

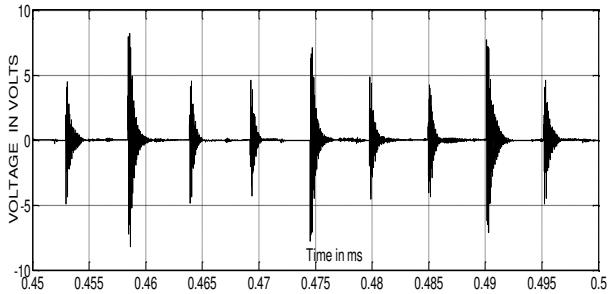

Figure-11. Cable screen output voltage (500 meter).

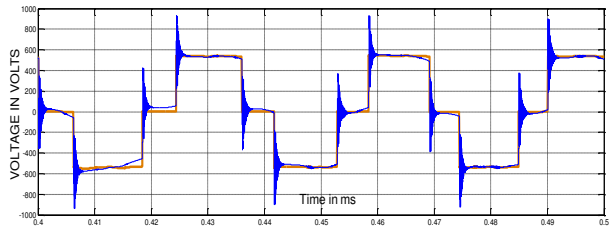

Figure-12. Cable end input and voltage line to line (500 meter).

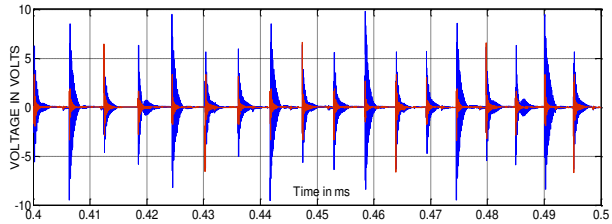

Figure-13. Cable screen input and output voltage (750 m).

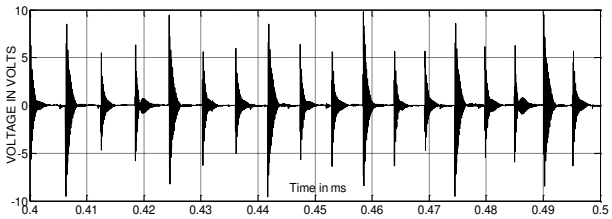

Figure-14. Cable screen output voltage (750 meter).

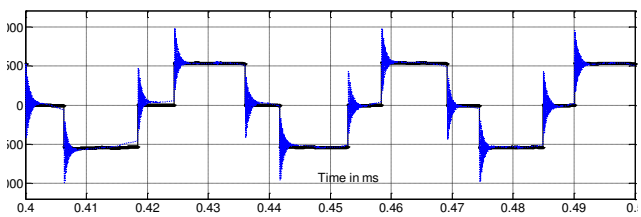

Figure-15. Cable end input and output voltage line to line (750 meter).

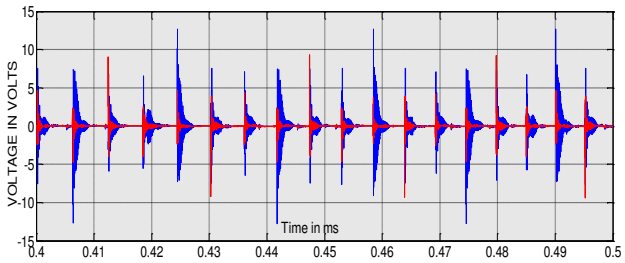

Figure-16. Screen input and output voltage in 1000 meter cable length.

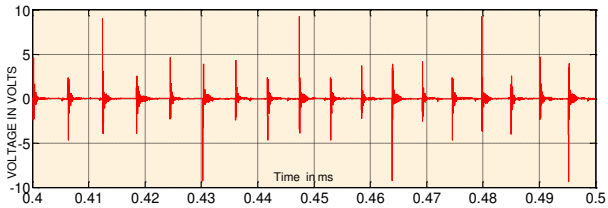

Figure-17. Screen input voltage in 1000 Meter cable length.

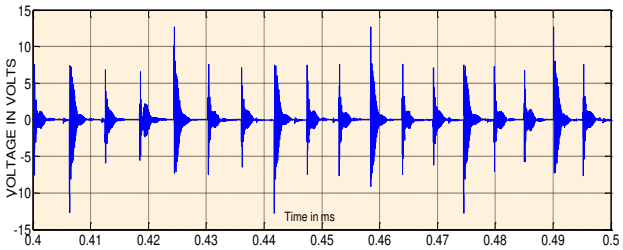

Figure-18. Screen output voltage in 1000 meter cable length.

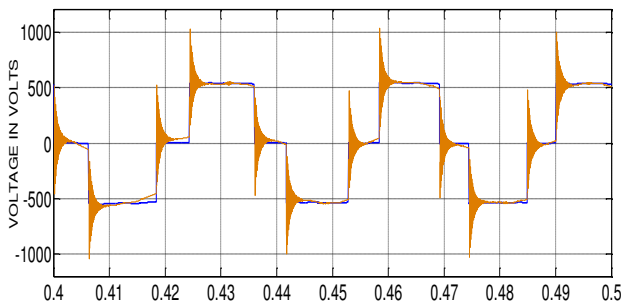

Figure-19. Cable end input and output voltage (1000 meter).

CONCLUSIONS

This paper presents a method of modeling and simulation of the long fed power cables in variable frequency drives (VFD) system where in critical cable parameters such as cable resistance, inductance, capacitance as well as screen resistance, inductance, capacitance are considered in the new power cable model. . The proposed model allows both series inductance and shunt capacitance are accounted in the power cable equivalent model. The cable parameters both series inductance and shunt capacitance are considered with different length of the cable. However, if the new coupling models are connected between induction motor and VFD drives. The cable screen voltage, cable end input output line-line voltages are measured for both the end of input and output cable terminal. The cable output reflected voltage magnitude is increased double dc link voltage and also increased for increasing the cable length. Using MATLAB Simulink model, the measured results are verified and proved that screen voltage increases the length of the cable as well increase the cable parameter. The comparison of the new power cable model is presented in technical literature, confirms the goodness of the proposed method.

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