High frequency Lumped parameter model for EMI Problems and over voltage Analysis of induction motor

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Abstract: *In this paper a novel high frequency lumped model of Induction motor is presented that is suitable for prediction of terminal over voltage analysis and Electromagnetic Interference (EMI) problems and common mode (CM) current. The parameters of the proposed model are defined by asymptotical method using differential and common mode impedance measurements. This proposed model also can be used to predict and solve the high frequency problems and designing EMI filters to improve Electromagnetic Compatibility (EMC) limitation in cable fed motor-drive system. The proposed model considered accurate simulation of both differential and common mode behavior in the EMI-frequency range from 100 Hz to 30MHz. This model has been validated by differential mode (DM) and common mode (CM) test measurements in both magnitude and phase which measurement have been done using an impedance analyzer.* There is a very good accordance between the experimental results and simulation results of the proposed model in both magnitude and phase.

Key words: *common mode (CM) current, EMI, induction motor, high frequency, over voltage.*

1. Introduction

Induction motors are fed by static power converters that commonly used in a large number of industrial applications due to their flexibility and attractive performances.

The uses of Modern adjustable speed drive to drive induction motors cause two main problems in such systems: 1) transient over voltages at the motor terminals and 2) Electromagnetic interference (EMI) problems [1-3].

Fast switching can lead to the reflected wave phenomenon, and high-frequency leakage currents through the system's leakage impedances. Reflected waves result in transient over voltage at the motor terminals, and the high-frequency leakage currents result in electromagnetic interference (EMI) [3-5].

The magnitude of the overvoltage depends on the pulse rise time and the characteristics and length of the cable. Belong to length of cables the maximum peak over-voltage is twice the DC bus voltage and can sometimes exceed 2 (p.u.). This overvoltage at the motor terminals, cause an intense electrical stress in the insulation system [6-8].

in order to improving of system performance, prediction and prevent of these high frequency problems, malfunction and fault of system, it is necessary to be state an high accurate model of high frequency induction motor model.

Many investigations into high-frequency induction motor modeling were recently reported in [8-23]. . Accurate high-frequency induction motor modeling plays a significant role in analyzing the cable-fed induction motor drive system overvoltage and EMI problems which were described in.

The performed investigation shows that high-frequency behavior of induction motor can be modeled with a lumped parameter equivalent circuit [9-14].

In this paper a new lumped model for induction motors with a high accuracy is presented. Parameters of the proposed model are defined by asymptotical method using differential and common mode impedance measurements which are presented following in detail. The outstanding merit of the proposed model is the realization of both magnitude and phase of the motor characteristic.

Electromagnetically couple between phases and winding is contained naturally in this model because of the proposed model parameters are defined with DM and CM test of induction motor.

At last prediction of terminal overvoltage and common mode current have been simulated.

2. Proposed High Frequency Induction Motor Model

Proposed per-phase high frequency circuit model for induction motor are shown in Fig. 1. The proposed model is based on lumped parameters. Two main branches are involved in this high frequency model: 1) stator winding to motor frame branch and 2) stator winding turn to turn branch. In the proposed model phase to frame branches in two ends of the motor winding are not the same.

By assuming a wye connection of three single-phase circuits of proposed model, parameter of the high frequency equivalent circuit model can be obtained.

However, this proposed three-phase high frequency model, which gives an equivalent wye-connected circuit model, is valid independent of the actual stator windings (i.e., delta or wye connection).

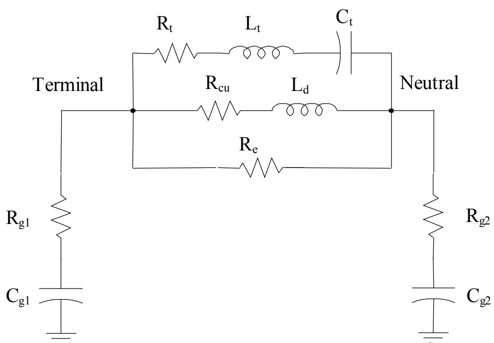

Fig. 1. Proposed per-phase motor winding model

As illustrated in Fig. 1, C_{g1} and C_{g2} are parasitic capacitance of stator winding to motor frame, R_{g1} and R_{g2} are resistance of capacitances current paths. Iron loss presented by R_e, R_{cu} calculating copper loss of the stator winding and L_d shown the leakage inductance of the stator winding. Parameters R_t, L_t, and C_t are responsible to second resonance in the motor frequency characteristic which may be cause by capacitances of inter-turn stator windings and skin effect.

Two basic type measurements conducted on the induction motor in star connection (common mode and differential mode test) are needed [16] to identify and extract the high frequency model parameters.

The detailed measurements setup, test procedures, and proposed model parameterization have been described in the next sections.

3. Measurement setup and experimental result

The motor winding impedances frequency response characteristics (as magnitude and phase) have been measured in the range from 100 Hz to 30 MHz using a network analyzer HP/Agilent 4395A Rev1.04 as shown in Fig. 2.

The motor under study is a four-pole, star connected, 9.3-kW, 400Y/230Δ V, Nerimotori type 132ML industrial induction motor. For performing these tests the rotor is locked and the power supply cable is disconnected.

3.1. Differential Mode Impedance measurement

In this paper a novel differential mode test is presented, which configuration and its associated measured impedance are shown in Fig. 3.

In proposed differential mode test, the two phases of stator windings are connected in series and impedance is measured between two terminals. L_{zu} shows the inductance of motor internal feed lines and connectors.

Fig. 2. Experimental set up for measurements

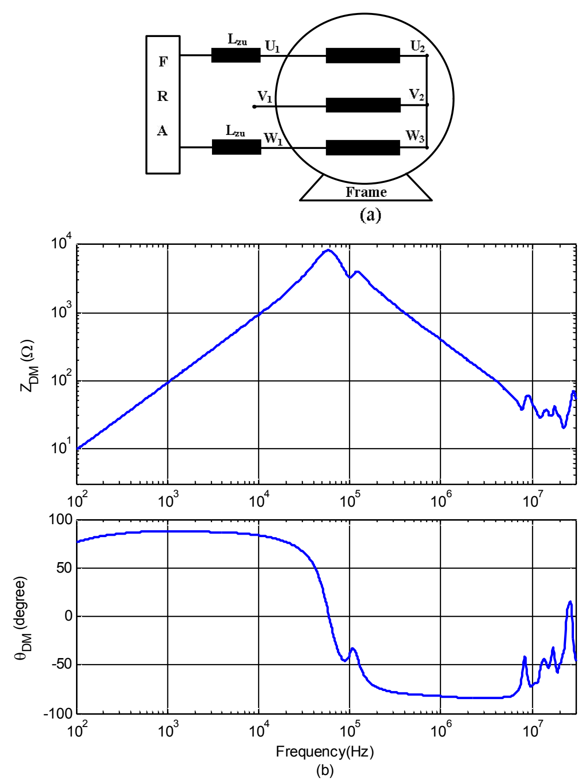

Fig. 3. Proposed differential mode configuration (Z_{DM2}) and its experimental result: (a) Connection diagram (b) Measured impedance (magnitude and phase)

3.2. Common Mode Impedance Measurement

A novel common mode test is presented in this paper, which configuration and its associated measured impedance are shown in Fig. 4.

In proposed common mode test, in terminal side three stator windings are connected to each other and in neutral side only two stator winding are connected to each other. The common mode impedance is measured between terminal and frame.

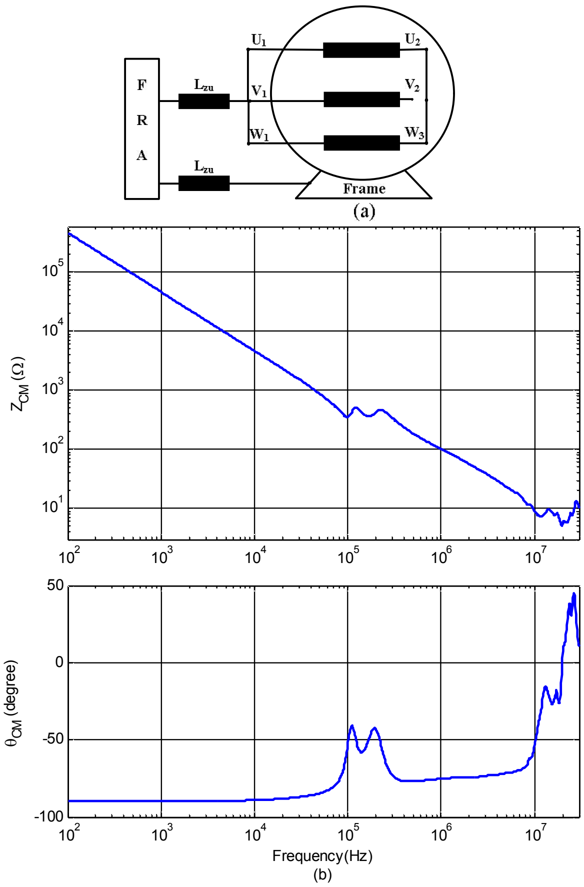

Fig. 4. Common mode test configuration (Z_{CM}) and its measurement result: (a) Connection diagram (b) Measured impedance (magnitude and phase)

3.3. Model Parameters Derivation

The parameters of the proposed circuit of each phase of the induction motor (see Fig. 1) are obtained by identification procedures and experimental data. At low and high frequency, In common mode configuration, tested motor behaves as a capacitive dominant series impedances which respectively C_{total} and C_{HF} can be evaluated from measured common mode impedance characteristic. At low frequency, in differential mode configuration, tested motor behaves as an inductive dominant series impedances which L_{DM} can be extracted from measured differential mode impedance characteristic and the influence of C_{gl} cause the differential impedance characteristic at high frequency behaves as a capacitive dominant series. The resistance of the stator winding (R_{cu}) limits the phase current at low frequencies. The value of this parameter is less than of 5Ω.

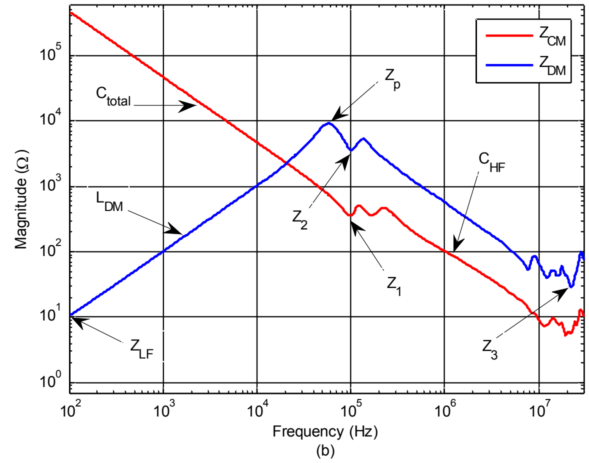

Fig. 5. Measured impedances of induction motor

The behaviors of the impedance characteristic of the test configuration have been analyzed, now the parameters of the motor can be calculated. The parameters of the high frequency model are calculated using measured differential and common mode impedance characteristic as fallow [2, 8-10]:

$$R_{cu} \approx \frac{1}{2}|Z_{LF}|\cos(\theta_{LF}) \tag{1}$$

$$C_{g1} \approx \frac{1}{3}C_{HF} \tag{2}$$

$$C_{g2} \approx \frac{1}{3}(C_{total} - C_{HF}) \tag{3}$$

$$L_{CM} \approx \left(12\pi^2 C_{g2} f_{z1}^2\right)^{-1} \tag{4}$$

$$R_e \approx \frac{1}{2}|Z_p| \tag{5}$$

$$R_{g1} \approx \frac{1}{2}|Z_{Z3}| \tag{6}$$

$$L_d \approx L_{CM} + \frac{4}{9}L_{DM} \tag{7}$$

$$R_{g2} \approx \frac{1}{3}|Z_{Z1}| \tag{8}$$

$$C_t \approx \frac{1}{6}\left(C_{g1} + C_{g2}\right) \tag{9}$$

$$L_t \approx \frac{1}{C_t}\left(\frac{1}{2\pi f_{Z2}}\right)^2 \tag{10}$$

$$R_t \approx 3|Z_{Z2}|\cos(\theta_{Z2}) \tag{11}$$

$$L_{zu} \approx 3\left(16\pi^2 C_{g1} f_{Z3}^2\right)^{-1} \tag{12}$$

where f_{z1} and Z_{z1} are identified from first zero point of common mode impedance characteristic and Z_p, Z_{z2}, f_{z2}, Z_{z3}, and f_{z3} respectively are identified from first pole point magnitude, second and third zero point magnitude and frequency of differential mode impedance characteristic. These prominent points are shown in

Figure 5 on CM and DM impedances measured. The value of capacitance "C_{total}, and C_{HF}" in the right hand side of the (2), and (3) calculated by relation $C = \frac{1}{2\pi f Z}$ and the value of the inductance "L_{DM}" in the right hand side of the (7) calculated by relation $L = \frac{Z}{2\pi f}$.

Using (1)-(12) an initial value for the proposed circuit parameters are extracted by asymptotical method. The final optimum values of the equivalent circuit parameters are obtained using Genetic Algorithm.

These optimized values of the high-frequency parameters are listed in Table I.

TABLE I
PARAMETERS VALUE OF THE PROPOSED HIGH FREQUENCY INDUCTION MOTOR MODEL

Parameter	Optimized value
R_t	3.54 kΩ
L_t	13.39 mH
C_t	172.76 µF
R_{cu}	1.31 Ω
L_d	8.01 mH
R_e	5.15 kΩ
R_{g1}	16.06 Ω
C_{g1}	581.03 µF
R_{g2}	7.21 Ω
C_{g2}	469.67 µF
L_{zu}	44.02 nH

3.4. Model Validation

In order to validate the proposed model described in this paper, a series of measurements were carried out on the 9.3- kW industrial induction motor by using a Network Analyzer (HP/Agilent 4395A) in frequency domain. The experimental setup and connection diagram of the motor winding have been described previously and are illustrated in Figures 3 and 4.

The simulation and experimental results are obtained (for described system) to validate the proposed motor winding model.

The model has been validated by differential mode (DM) and common mode (CM) test measurements in both magnitude and phase within the frequency range from 100 Hz to 30 MHz.

As shown in Figure 6, superimposing the experimental results and simulation results of the proposed model verifies that there is a very good accordance between them in both magnitude and phase.

3.5. Prediction and Application of proposed model

Since both of the differential mode (DM) and common mode (CM) experimental configuration are used in this proposed model, result in transient over voltage and CM mode Current respectively can be predicted.

Cable-fed induction motor drive system which is generally composed of a drive feeding an induction motor through a cable is shown in Fig. 7.

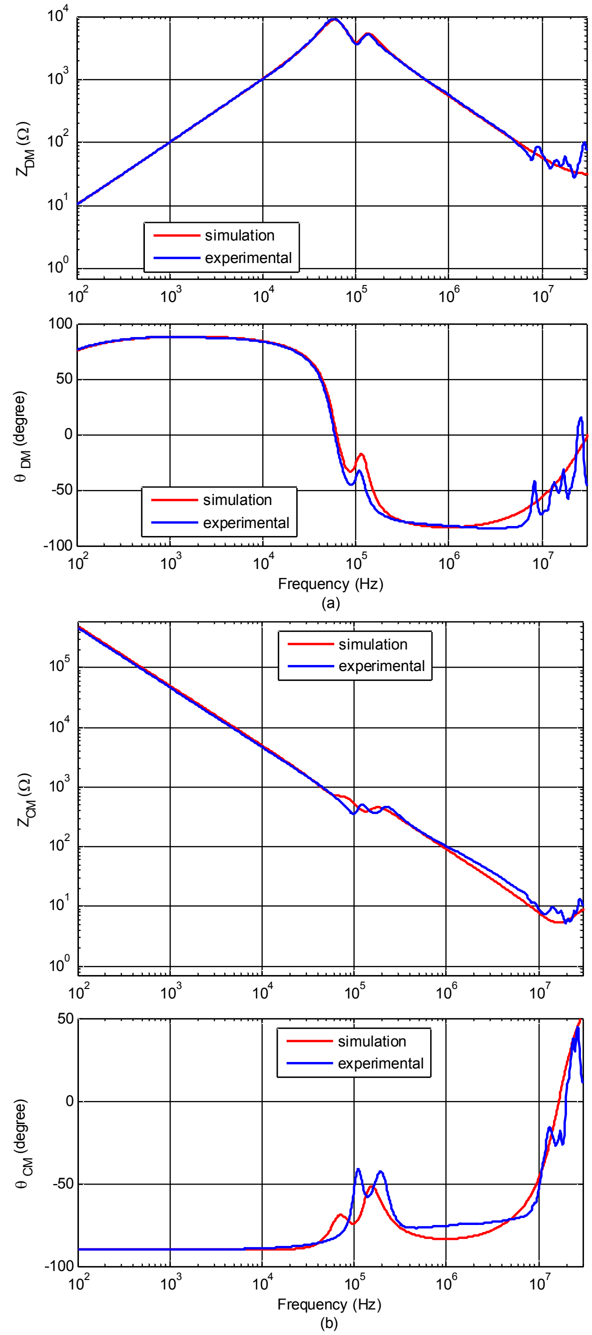

Figure 6. Comparison between experimental and simulation result for DM and CM: (a) Z_{CM}, (b) Z_{DM}

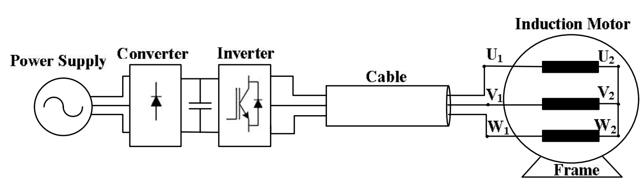

Fig 7. A typical cable-fed induction motor drive system.

The time domain simulation of the cable fed induction motor drive system is carried out with Electro Magnetic Transient Program (EMTP). Pulse width modulation (PWM) source inverter, and PVC-insulated cable with conductor area of 6 mm^2 are used to simulate transient voltage at the motor terminal and common mode current waveforms. The proposed high frequency model for 9.3kw induction motor was used in this simulation.
To demonstrate the overvoltage and common mode current phenomena on the considered motor drive system with a 300-m cable, the simulated line-to-line voltages at the motor terminal and the inverter side, and common mode current respectively are shown in Figs. 8-11.

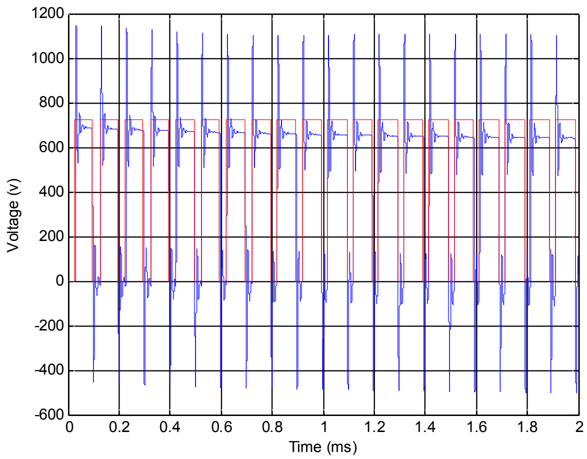

Fig. 8. Simulated transient line to line voltage waveforms at the motor terminals for 300-m cable in proposed model (blue is motor terminal voltage, and red is inverter voltage)

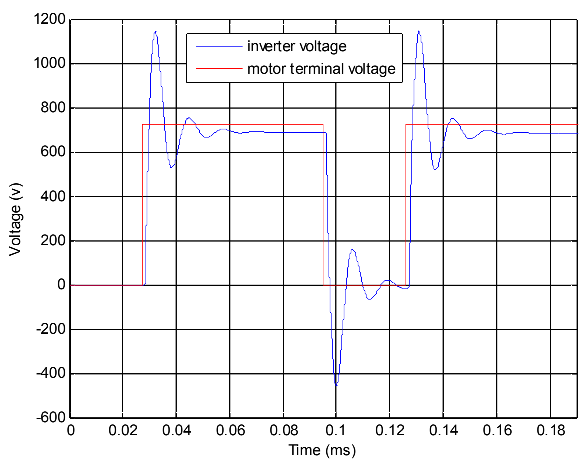

Fig. 9. Zoom in transient voltage in Fig. 8 for more clearly.

3.6. Conclusion

In this paper, a high frequency modeling of Induction motor is presented that is suitable for prediction of terminal over voltage analysis and Electromagnetic Interference (EMI) problems and common mode (CM) current.
In order to identify the parameters of the proposed model, two novel experimental tests, common mode and differential mode tests configuration, have been done.

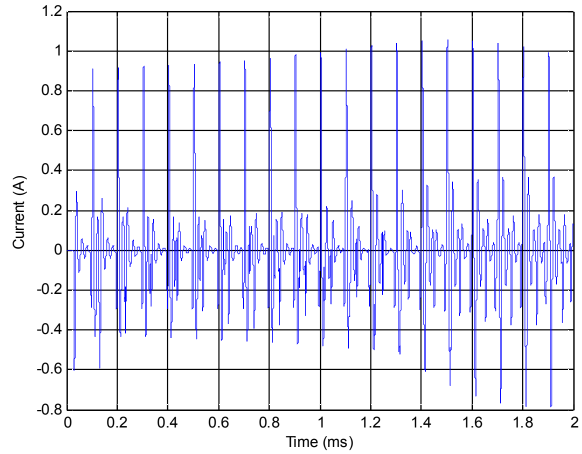

Fig. 10. Simulated common mode current waveforms at the motor terminals for 300-m cable in proposed model

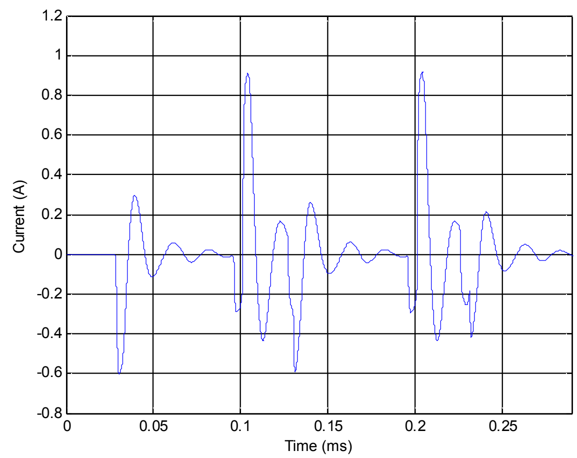

Fig. 11. Zoom in common mode current in Fig. 10 for more clearly.

Parameters of the proposed equivalent circuit were initially calculated by asymptotical method, in which the parameters of the model are derived from the observation of the variations of the motor impedance with the frequency, and then tuned to their optimum values using GA.
This proposed model accord to the measurement result in both phase and magnitude in the frequency range from 100 Hz to 30 MHz.
Since both of the differential mode (DM) and common mode (CM) experimental configuration are used in this proposed model, result in transient over voltage and CM mode current respectively can be predicted and following them this model can be suitable for designing EMI filters and insulated system. These models can also be used for the diagnostic of the defects of the motors. Finally these predictions of current and voltage have been simulated and outputs of these predictions are shown in Figs. 8-11.

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