Optimized High Frequency Lumped Parameters Model of Induction Motor Using Genetic Algorithm (GA)

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Abstract:
In this paper an optimized high frequency lumped model of Induction motor is presented. Model parameters are identified and optimized using Genetic Algorithm (GA). A novel model and approach in an improved high frequency based on GA for parameter identification are used. At first, parameters are limited and then fitted using GA for best fitting. The proposed model considered accurate simulation of both differential and common mode behavior in the EMI-frequency range from 100 Hz to 30MHz. Model parameters which extracted from GA are compared with experimental data in both magnitude and phase at the same time and results show a good accordance between the experimental results and simulation results of the proposed model. A least mean square (LMS) method was used with a GA optimization method to solve the identification problem. The proposed model is suitable to obtain the simulation models to predict high frequency conducted Electromagnetic Interference (EMI), over voltage on terminated motor and common mode current in cable fed induction motor.

Keywords: Electromagnetic Interference (EMI), Genetic algorithm (GA), induction motor, lumped parameter, modeling.

1. Introduction

Advances in semiconductor device improved the performance of Adjustable Speed Drive (ASD) in cable fed induction motors which are used widely in industry. The uses of Modern ASD to drive induction motors cause two main problems in such systems: (I) transient over voltages at the motor terminals and (II) Electromagnetic interference (EMI) problems [1, 2].

High speed switching in power converter causes continuous voltage pulse and increase the carrier frequency in current. When an induction motor is connected to an inverter through a cable, these waves current and voltage are reflected at the cable ending connected in motor terminal because of mismatching in cable and motor surge impedances and these phenomena can lead to over voltage at the induction motor terminal. Reflected waves result in transient over-voltage at the motor terminals, commonly modeled by a single-line circuit known as differential mode (DM). These over-voltages can impose electric stress on inter-turn stator windings insulation, in particular in the early turns. The over-voltage phenomenon can also cause partial discharges in cable fed induction motor thereby decreasing its lifetime [2-5].

High frequency switching in power electronic devices induce high frequency currents, namely as common mode (CM) and differential mode (DM) currents, flowing through the parasitic capacitances of the cable, motor and inverter [6, 7]. Common mode (CM) currents result in EMI problems, commonly modeled by a single-line circuit known as common mode (CM). These parasitic currents

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can lead to EMI problems malfunction of ground-fault protection and motor bearing failures in the cable fed induction motor system [5].

Increasing in switching rate can lead to these problems be more observable. Therefore, an accurate high frequency model of cable and induction motor are needed to predict and analyze these phenomena.

Many investigations are done on modeling of high frequency of induction motor for EMI and overvoltage analysis [8-21]. In [11-16] two branches in the two end of winding are assumed to be the same, but in more complete model [17, 18, 20, 21] they are different.

In many papers (e.g. [12, 16, 18, 19]), the parameters of high frequency models were tuned by means of a non-intelligent (trial and error) method, the authors propose here an optimization using genetic algorithms (GA). Several authors have proposed model optimization techniques (e.g. neural network, GA, particle swarm optimization (PSO)) for parameters identification for induction motor [22-25]. However, most of these models were not proposed for HF behavior.

In this paper, a high frequency model of induction motor is proposed based on asymptotical method and model parameters are identified and optimized using GA. In the proposed model, the skin and proximity effect are considered. For validation and determination of parameter of the proposed motor, two new test configurations are proposed and finally the parameters are optimized using GA. Proposed motor in this paper are validated in DM and CM tests in both magnitude and phase. This paper containes two sections. The first model is proposed and its parameters are identified and optimized by GA and then the proposed model has been validated.

2. Proposed High Frequency Model

Proposed per-phase high frequency circuit model for induction motor is shown in Figure 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 is not the same.

As illustrated in Figure 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 is presented by R_e, R_{cu} calculate copper loss of the stator winding and L_d shows 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 a cause by capacitances of inter-turn stator windings and skin effect.

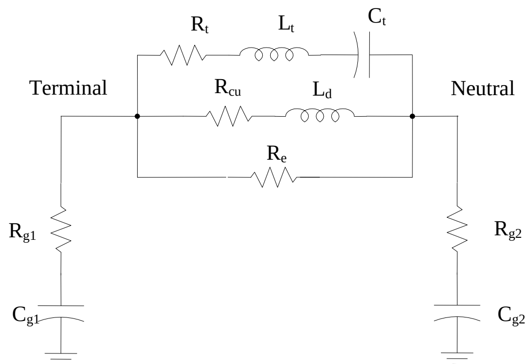

Fig (1): Proposed per-phase motor winding model

Two basic type measurements conducted on the induction motor in star connection (common mode and differential mode test) are needed [13] to identify and extract the high frequency model parameters. By assuming a wye connection of three single-phase circuits of proposed model, parameters 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).

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 Figure 2. The motor under study is a four-pole, star connected, 9.3-kW, 400Y/230Δ V, Nerimotori type 132ML industrial induction motor.

To perform these tests, the motor is stationary and the power supply cable is disconnected.

Fig (2): Experimental set up for measurements

3.1. Common Mode Impedance Measurement

A novel common mode test is presented in this paper which configuration and its associated measured impedance are shown in Figure 3.

In proposed common mode test, in terminal side three stator windings are connected to each other and in neutral side only two stator windings are connected to each other. The common mode impedance is measured between terminal and frame. L_{zu} shows the inductance of motor internal feed lines and connectors.

3.2. Differential Mode Impedance Measurement

Example: In this paper a novel differential mode test is presented, which configuration and its associated measured impedance are shown in Figure 4.

In the proposed differential mode test, 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.

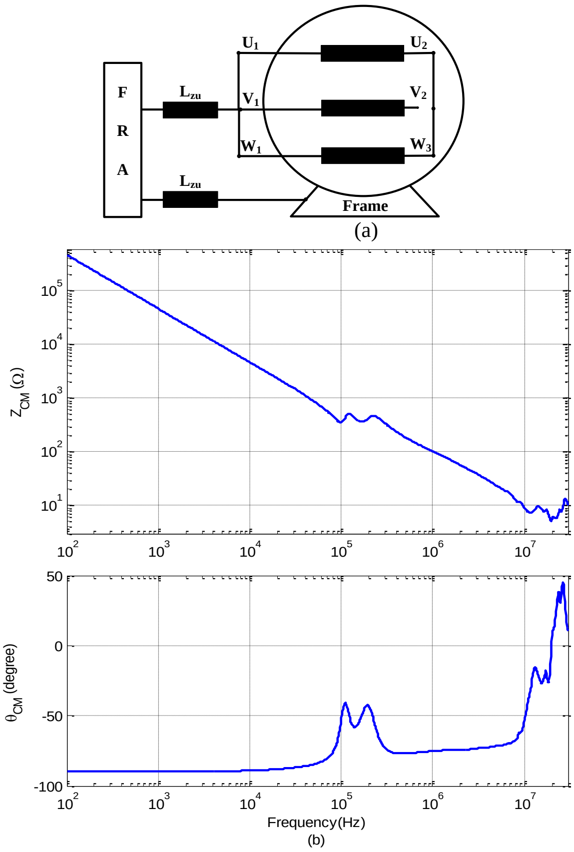

Fig (3): Proposed common mode test configuration (Z_{CM}) and its measurement result: (a) Connection diagram (b) Measured impedance (magnitude and phase)

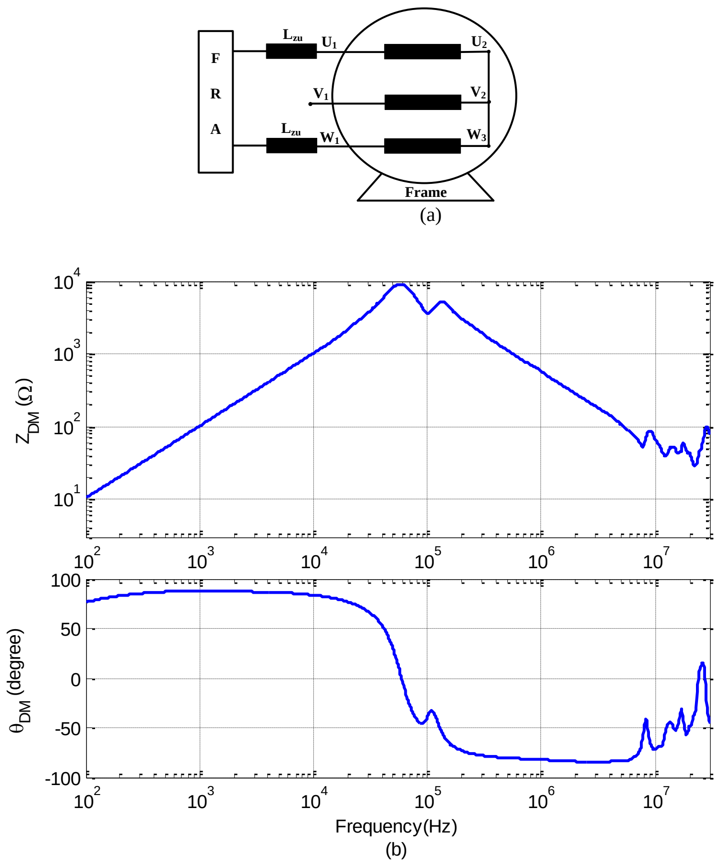

Fig (4): Proposed differential mode configuration (Z_{DM}) and its experimental result: (a) Connection diagram (b) Measured impedance (magnitude and phase)

4. Model Development And Parameter Derivation

Proposed induction motor parameters (see Figure 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 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 impedance which L_{DM} can be extracted from measured differential mode impedance characteristic and because of effect of C_{g1} the differential impedance characteristic at high frequency behaves as a capacitive element. 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.

The behaviors of the impedance characteristic of the test configuration have been analyzed, now the parameters of the motor can be estimated.

The initial value of the proposed circuit parameters can be calculated according to the equations summarized in Appendix A, 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.

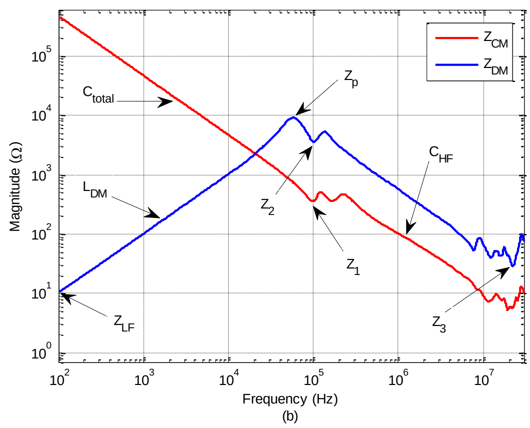

Fig (5): Measured impedances of induction motor

4.1. Optimization Of The Model Using GA

The GA is an optimization and search technique based on the principles of genetics and natural selection. The method was developed by John Holland (1975) over the course of the 1960s and 1970s and finally popularized by David Goldberg [26].

The basic procedure of GA in this paper has been described in the following.

4.2. Chromosome Encoding

Each individual of population, called chromosome, is a candidate solution to an optimization problem. Each individual contains variables, called gen, represented in real values. In encoding procedure each gen of chromosome belonges to each parameter of models, therefore each chromosome is a potential solution. This encoding procedure can be seen in Figure 6.

R_t	L_t	C_t	R_{cu}	L_d	R_e	R_{g1}	C_{g1}	R_{g2}	C_{g2}	L_{zu}

Fig (6): Chromosome encoding

4.3. Population Initialization, Fitness Value, And Selection

By estimating each parameter which are described later, the parameters variation range are limited (as shown in table I) and therefore search space for the problem solution are more less. This is a good advantage of this procedure. Having this limitation on parameters variation, range the set of initial population which is generated randomly.

During each successive generation, a proportion of the existing population is selected to breed a new generation. Individual solutions are selected through a fitness-based process, where fitter solutions (as measured by a fitness function) are typically more likely to be selected. Certain selection methods rate the fitness of each solution and preferentially select the best solutions.

The fitness function is evaluated as the least mean square (LMS) error of common mode and differential mode, which is shown as in:

$$FF = e_{DM}^2 + e_{CM}^2 \qquad (1)$$

4.4. Crossover And Mutation

After generated initial population, the next step is to generate a second generation population of solutions from those selected through genetic operators: crossover (also called recombination), and mutation. In the next step of this procedure, crossover and mutation are used for next generation. These processes ultimately result in the next generation population of chromosomes that is different from the initial generation. Generally, the average fitness will be increased by this procedure for the population, since only the best organisms from the first generation are selected for breeding.

In order to cover all the search space, the crossover rate is chosen with high values and in order to avoid convergence problems, the mutation rate value is chosen low.

The flowchart of the GA for identifying parameters of the proposed model is shown in Figure 7. The final optimum values of the equivalent circuit parameters are obtained using Genetic Algorithm. The optimized values of the high frequency parameters which obtained by the mentioned method are given in Table I.

In the next section comparison between experimental result and equivalent circuit simulation result will be shown for validation.

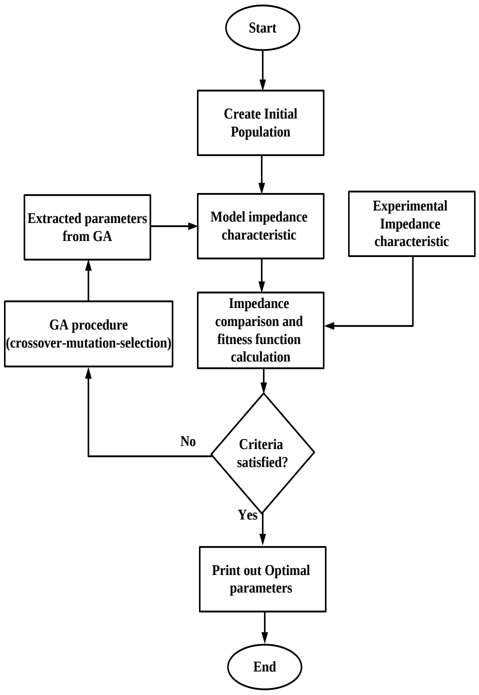

Fig (7): Flowchart of the Genetic Algorithm

Table (1): Optimized Value For Parameters Of The Proposed High Frequency Induction Motor Model

Parameter	Variation bound	Optimized value
Rt	2-4 kΩ	3.54 kΩ
Lt	2-20 mH	13.39 mH
Ct	100-400 μF	172.76 μF
Rcu	0.1-4 Ω	1.31 Ω
Ld	7-20 mH	8.01 mH
Re	4-7 kΩ	5.15 kΩ
Rg1	10-30 Ω	16.06 Ω
Cg1	400-700 μF	581.03 μF
Rg2	1 mΩ-1 kΩ	7.21 Ω
Cg2	400-750 μF	469.67 μF
Lzu	50-100 nH	44.02 nH

5. 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 8, 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.

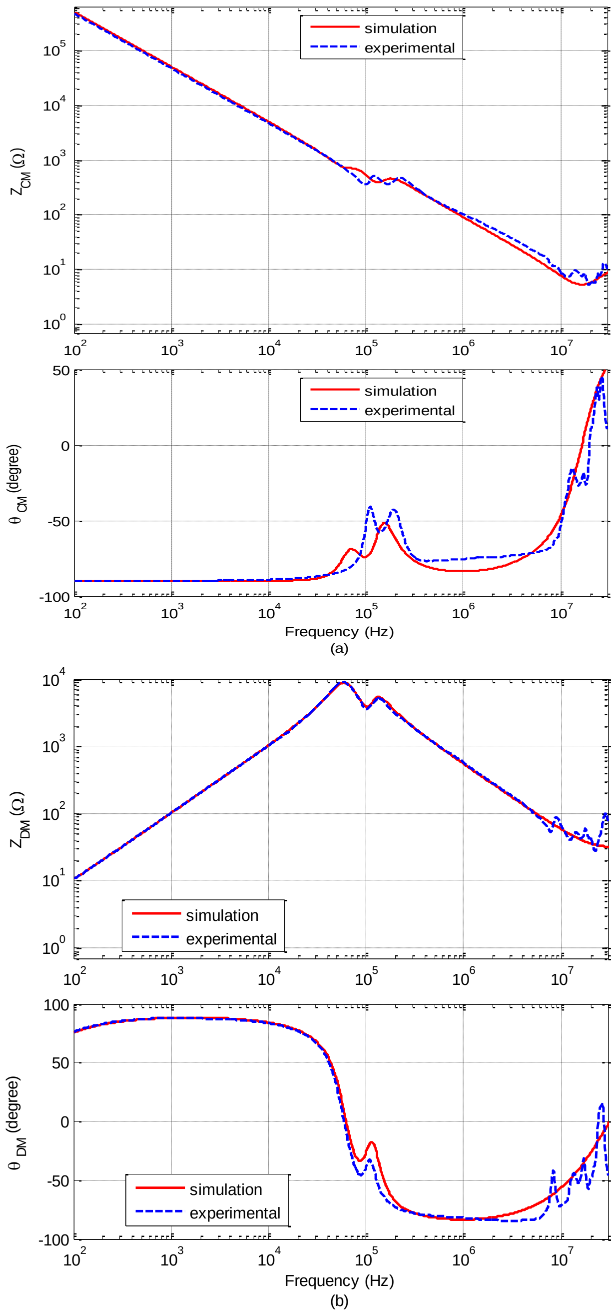

Fig (8): Comparison between experimental and simulation result for DM and CM: (a) Z_{CM}, (b) Z_{DM}

6. Conclusion

In this paper, a high frequency lumped modeling of Induction motor is presented, and Model parameters are identified and optimized using GA.

In order to identify parameters of the proposed model, at first initial values of the parameters have been estimated and then by limiting variation range parameters, optimized them using GA for best fitting. In order to extracting equations and following, it determined initial value of proposed model parameters, measurements of magnitude and phase impedance of the common mode and differential mode motor configuration have been done.

On the other hand, a novel configuration test have been done and presented in this paper.

Two state-space representations for the two different impedance configurations have been developed and tuned an equivalent circuit impedance characteristic using a GA optimization procedure: The parameters of the motor windings in differential mode and common mode high frequency models have been selected and optimized by 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 insulated system. These models can also be used for the diagnostic of the defects of the motors.

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Appendix A

The parameters of the high frequency model are calculated using measured differential and common mode impedance characteristic as fallow [12, 18-20]:

$$C=\frac{1}{2\pi f Z} \tag{A1}$$

$$C_{g1}\approx\frac{1}{3}C_{HF} \tag{A2}$$

$$C_{g2}\approx\frac{1}{3}\left(C_{total}-C_{HF}\right) \tag{A3}$$

$$C_{t}\approx\frac{1}{6}\left(C_{g1}+C_{g2}\right) \tag{A4}$$

$$R_{cu}\approx\frac{1}{2}\left|Z_{LF}\right|\cos(\theta_{LF}) \tag{A5}$$

$$R_{e}\approx\frac{1}{2}\left|Z_{p}\right| \tag{A6}$$

$$R_{g1}\approx\frac{1}{2}\left|Z_{Z3}\right| \tag{A7}$$

$$R_{g2}\approx\frac{1}{3}\left|Z_{Z1}\right| \tag{A8}$$

$$R_{t}\approx 3\left|Z_{Z2}\right|\cos\left(\theta_{Z2}\right) \tag{A9}$$

$$L=\frac{Z}{2\pi f} \tag{A10}$$

$$L_{CM}\approx\left(12\pi^{2}C_{g2}f_{z1}^{2}\right)^{-1} \tag{A11}$$

$$L_{d}\approx L_{CM}+\frac{4}{9}L_{DM} \tag{A12}$$

$$L_{t}\approx\frac{1}{C_{t}}\left(\frac{1}{2\pi f_{Z2}}\right)^{2} \tag{A13}$$

$$L_{zu}\approx 3\left(16\pi^{2}C_{g1}f_{Z3}^{2}\right)^{-1} \tag{A14}$$

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