A Methodology to Develop Induction Motor Model from Modal Measurements for EMTP

Asha SHENDGE* and Naoto NAGAOKA*

(Received October 19th, 2012)

Electro-magnetic transient program (EMTP) is worldwide used for transient analysis simulation. It is well known it cannot deal with modal value directly. Therefore, for transient analysis it is necessary to convert measured modal impedances into phase domain. The over-voltage phenomenon is usually described using the traveling wave and reflection phenomena due to control in variable speed drive system consists of pulse width modulated (PWM) inverters. A motor winding may partially discharge due to an inverter surge giving a significant impact on its insulation, and lead to a breakdown.A soft switching technology has been developed to suppress the surge voltage. It requires to evaluate the surge in advance. For this, an accurate prediction of the surge voltages at the terminals of the motor becomes very significant. Models for the connecting cable and the motor are required for the prediction. This paper emphasize on induction motor model using the theory of natural modes of propagation. The methodology to develop motor model for EMTP is studied and discussed in detailed.

Key words: Induction Motor, Modal Measurements, Inverter Surge, EMTP

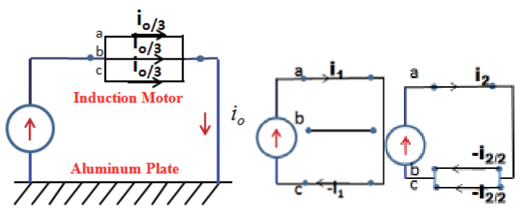
1. Introduction

An induction motor (IM) is an asynchronous alternating current machine that consists of a stator and a rotor. An induction motor is widely used because of the rugged construction and moderate cost. Recently, the variable speed drives produced mostly consist of brushless motors and power converters. In many cases, the squirrel cage induction motor is used and it is controlled by a voltage fed pulse width modulated (PWM) inverter. The motor is controlled via the PWM inverter by keeping the amplitude and frequency of the reference (sinusoidal) signals constant according to the desired output speed. Thus, maintaining constant magnetic flux in the motor. For micro-surge due to reflection and refraction at motor terminal voltage peaks are developed. It is necessary to have accurate induction motor model in consideration of frequency dependent effect, as motor resistance, inductance and capacitance are frequency dependent due to transient phenomena. There are several studies carried out by different authors to simulate peak voltage at motor terminals due to inverter surge [1 ~ 5]. In this paper three-phase induction motor model is developed based on natural mode measurements in steady state. The analytical calculations are carried out using theory of resonance in motor winding. The modal to phase transformation are implemented using a computational tool such as Maple, which provides template, a convenient method to analyze matrix calculations. Thus, suitable induction motor model is developed for Electro-Magnetic Transient Program (EMTP).

*Department of Power System Analysis, Faculty of Science and Engineering, Doshisha University, Kyo-tanabe, Kyoto 610-0321
Telephone: +81-774-65-6690, Fax: +81-774-65-6849, Email:ashashendge@gmail.com

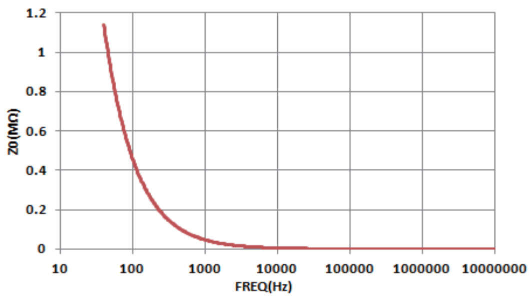
2. Experimental set up

A 3 phase, 2.2 kW, 50 Hz, 200 V, 9.2 A, 1430 rpm squirrel cage induction motor is used for analysis . Motor stator is connected in Delta connection. Motor is squirrel cage means rotor winding is shorted. Steady state measurements are carried out on de-energized condition for mode-0, mode-1 and mode-2. The current distribution for all propagation modes is as shown in Fig. 1. An impedance analyzer is used as input source (Agilent model 4294A 40Hz - 110MHz). Before measurements, calibration is done according to the manufacture's manual.

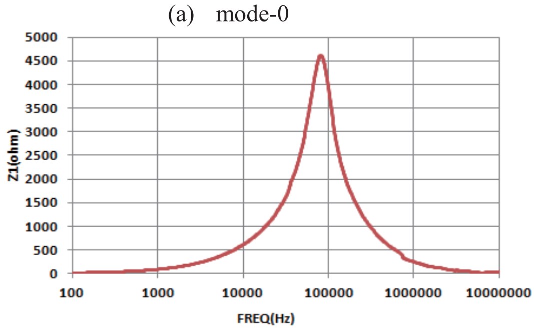


(a) mode-0 (b) mode-1 (c) mode-2
Fig. 1. Current distribution of three propagation modes

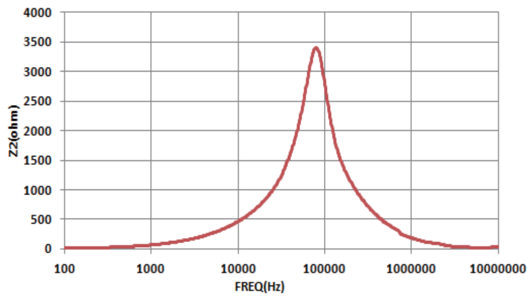
2.1. *Measured Results*



(a) mode-0



(b) mode-1



(c) mode-2
Fig. 2. Measured impedance of Motor

Fig. 2 (a), (b) and (c) are represents mode-0, mode-1 and mode-2 measured impedances, respectively. From measured waveform for mode-1 and mode-2 it is observed, the response is same as RLC parallel resonance and mode-0 response is same as discharging of capacitor.

2.2. *Analytical Calculation*

The analytical calculations are carried out based on well-known theory of resonance. For RLC parallel circuits at resonant condition, impedance is purely resistive *i.e.*

$$\boldsymbol{R} = \boldsymbol{Z} \qquad (1)$$

Resonant frequency ω in rad/sec is given by equation (2)

$$\omega_o = 1/\sqrt{LC} \qquad (2)$$

Quality factor Q is given by Equation (4)

$$\boldsymbol{Q} = \boldsymbol{R}\sqrt{C/L} \qquad (3)$$

Solving Equation (2) and Equation (3), we obtained capacitance as below

$$\boldsymbol{C} = \frac{1}{\omega_o \times \boldsymbol{R}} \qquad (4)$$

Once capacitance is calculated inductance can be obtained by Equation (3) as *R* and *Q* are known from measured waveform. Similarly, resonant frequency, and bandwidth *B* in rad/m can be calculated easily from ω_1 and ω_2.

$$\boldsymbol{B} = \omega_1 - \omega_2 \qquad (5)$$

where

$\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$

In addition, quality factor is given by

$$\boldsymbol{Q} = \frac{\omega_0}{\boldsymbol{B}} \tag{6}$$

Using Equation (5) and Equation (6) inductance and capacitance are calculated from measured data at resonant frequency. Table 1 and Table 2 represent the respective parameters.

Table 1: mode-1

ω_0(rad/m)	ω_1(rad/m)	ω_2(rad/m)	R(Ω)
509471.7	358686.8613	701894.9448	4617.94
B(rad/m)	Q	L(Henry)	C(Farad)
343208.1	1.48444	0.006106124	6.30949E-10

Table 2: mode-2

ω_0(rad/m)	ω_1(rad/m)	ω_2(rad/m)	R(Ω)
509471.7	358686.8613	701894.9448	4617.94
B(rad/m)	Q	L(Henry)	C(Farad)
343208.1	1.48444	0.006106124	6.30949E-10

From measurement of mode – 0, capacitance is 3.5 nF.

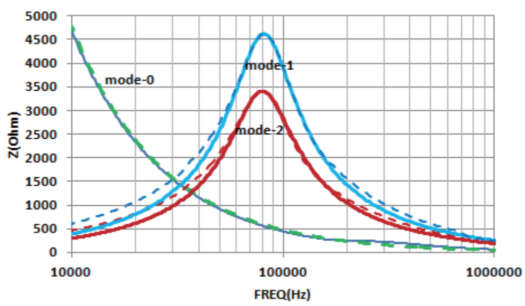


Fig. 3. Comparison of measured and analytical value

The capacitance and inductance obtained in Table 1 and Table 2 and mode-0 capacitance are used to plot against total frequency range**.** The Fig. 3 shows the reasonable agreement slight error observed due to approximation error.

2.3. *Equivalent Motor Model*

Fig. 4 illustrates a model circuit of an induction motor obtained from modal measurements. Resistance of inductor is very small. It is approximately equal to R_{dc} so it is neglected.

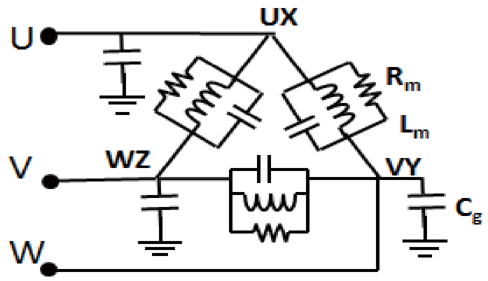


Fig. 4. Simple model circuit for an induction motor

From Fig. 4 circuit it can be observed three motor winding resistance R_m, inductance L_m, capacitance C_m are in parallel and three motor body to ground capacitance C_g.

3. Electro Magnetic Transient Program (EMTP) Simulation [6)]

Electro-magnetic transient program (EMTP) is worldwide used for transient analysis simulation. It is well known it cannot deal with modal value directly. Therefore for transient analysis it is necessary to convert measured modal impedances into phase domain.

3.1. *Transient Motor Model for EMTP*

Modal decomposition is given by the following matrices [7 ~ 8)].

$$Z_{mode} = [T_v]^{-1}[Z_{phase}]\,[T_i] \tag{7}$$

$$Y_{mode} = [T_v{}^{T}]\,[Y_{phase}]\,[T_v] \tag{8}$$

$$Z_{phase} = [T_v]\,[Zmode]\,[T_i]^{-1} \tag{9}$$

$$Y_{phase} = [T_i]\,[Zmode]\,[T_v]^{-1} \tag{10}$$

A wave propagation characteristic of multi-phase system is determined using the theory of natural modes of propagation. Generally, a symmetrical three-phase impedance and admittance matrices are transformed using the current transformation matrix $[T_i]$ and voltage transformation matrix $[T_v]$.

$$[T_i] = \begin{bmatrix} 1/3 & 1 & 1/2 \\ 1/3 & 0 & -1 \\ 1/3 & -1 & 1/2 \end{bmatrix}, \quad [Tv] = [T_i]_t^{-1} = \begin{bmatrix} 1 & 1/2 & \frac{1}{3} \\ 1 & 0 & -\frac{2}{3} \\ 1 & -1/2 & \frac{1}{3} \end{bmatrix} \tag{11}$$

From impedance, winding resistance and inductance can be calculated while from admittance capacitances can be calculated. *R*, *L* and *C* are incorporated in EMTP line constant routine. No load, resistance is converted to load condition by taking into account 6% core and mechanical loss. Table 3 represents the *R*, *L* and *C* obtained in phase domain calculated using above transformation.

Table 3: Phase domain parameters

R_m	L_m	C_m	C_g
600Ω	9.22mH	76.40μF	1.04nF

4. Conclusion

In this paper, induction motor model development for EMTP is discussed in detailed first time. To develop transient model, based on natural theory of modes measurements are carried out then steady state measured values are converted to transient state considering 6% core and mechanical loss. The induction motor model measured modal domain values are converted to phase domain for it's used in EMTP. The validity of model is investigated by the author by practical inverter surge measurements. It is observed using developed model the surge voltages at motor terminals can be represented accurately. The application model detailed in reference[9]. This model can be used for different switching surge simulations consist of induction motor.

The financial support provided by Japanese Government (MONBUKAGAKUSHO：Ministry of Education, Culture, Sports, Science and Technology-MEXT) Scholarship has made this research possible and it is greatly appreciated.

References

1) H. Paula, M. L. R. Chaves, D. A. Andrade, J. L. Domingos and M. A.A. Freitas, "A New Strategy for Differential Over voltages and Common Mode Currents Determination in PWM Induction Motor Drives," *IEEE* IEMDC '**05**, pp. 1075 – 1081, SanAntonio, Texas, USA.

2) L. A. Saunders, G. L. Skibinski, S. T. Evon and D. L. Kempkes, "Riding the Reflected Wave - IGBT Drive Technology Demands New Motor and Cable Considerations", *IEEE* **43**rd IAS Annual Meeting, P.75-84,09'96.

3) F. Moreira, T. A. Lipo, G. Venkataramanan and Bernet, S., "High frequency Modeling for Cable and Induction Motor Overvoltage Studies in Long Cable Drives," *IEEE Transactions on Industry Applications*, **38**, [5] pp. 1297 - 1306, 2002.

4) J. C. Oliveira, R. J. Paulsen, M. A. Amaral and D. Andrade, "Electrical Transmission System with Varia ble Frequency through Long Length Cable", *Offshore Technology Conf.*, Houston, May 1996.

5) M. Tsujitaka, K.Wada, H.Otsuka, M. Hirakata, N.Nagaoka,"Analysis of propagation of the inverter voltage and electric cable surge," *IEEJ* Trans PE, **B-126** [6], pp.771-777, 2006 (in Japanese).

6) W. Scott-Mayer, *EMTP Rule Book*, BPA, Portland Oregon, 1984.

7) L.M.Wedepohl, "Application of matrix methods to the solution of travelling-wave phenomena in polyphase systems", *Proceedings IEE,* **110,** pp. 2200-2212, Dec.63.

8) A.Ametani, "A general formulation of impedance and admittance", *IEEE Trans. PAS,* **99***,* [3], pp.902-908, May/June1980.

9) Asha Shendge, N.Nagaoka, "A Frequency Dependent Model of a Cabtyre Cable for Transient Analysis" *Journal of International Council of Electrical Engineering* (JICEE) Vol. 2 No. 4 pp. 449-455 Oct. 2012.