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Using Average DC-Pulse Response of Stator Current for Identification of Axial Flux Single-Phase Rotary Transformer Parameters

***Abstract**. Axial flux rotary transformers (AFRT) are used to transfer exciting signal into field winding of axial flux resolvers (AFRs). Accurate prediction of AFR dynamic performance is related to precise modelling and parameter identification of AFRT. This paper presents a new method based on DC-Pulse response of stator current for parameter identification of an AFRT. AFRT model was simulated with estimated parameters. Finally, the identified parameters were validated by comparing these simulation results with experimental test and 3D time stepping finite element analysis.*

***Streszczenie.** Artykuł przedstawia nową metodę identyfikacji parametrów transformatorów wirujących o strumieniu osiowym bazującą na odpowiedzi prądu stojana na skokową zmianę DC. Weryfikacji parametrów, dokonano poprzez wykorzystanie ich w badaniach symulacyjnych transformatora wirującego i porównanie wyników z badaniami eksperymentalnymi oraz trójwymiarową analizą metodą elementów skończonych. (**Identyfikacja parametrów jednofazowego osiowo transformatora wirującego o strumieniu osiowym na podstawie średniej odpowiedzi prądu stojana na skokową zmianę DC**)*

Keywords: Axial flux rotary Transformer, Parameter Identification, 3D time stepping finite element analysis, Axial flux resolver.
Słowa kluczowe: transformator wirujący o strumieniu osiowym, identyfikacja parametrów, trójwymiarowa analiza metodą elementów skończonych, resolwer o strumieniu osiowym

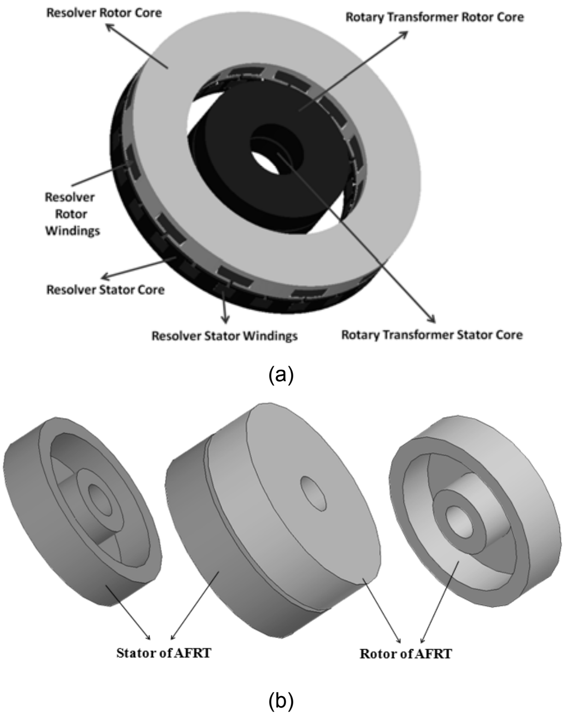
Introduction

Rotary transformer is widely used where brushless signal transmission is necessary. Rotary transformer can be constructed as radial flux and axial flux. The first one is used in conventional radial flux resolvers (RFRs) and the second one is used with AFRs. AFRs have lots of advantages against conventional RFRs. Because, although conventional radial flux (RF) encapsulated or pancake resolvers are used in high performance systems and inverter driven motors to provide accurate absolute position information, they suffer from a major drawback: static eccentricity (SE). This drawback causes a significant increase in resolver output position error (RPE) which could not be corrected electronically. Axial flux resolvers are strictly reliable against static eccentricity. So they are acceptable solution in high performance applications. Figures 1-(a) and 1-(b) show the structure of AFR and axial flux rotary transformer (AFRT), respectively.

Unlike conventional transformer in rotary transformer there is an air gap between primary and secondary windings. So they are called stator and rotor instead of primary and secondary.

As shown in Fig. 1-b, there are a cylindrical shaped iron core called stator with the primary coil fixed inside the stator, and another bobbin iron core called rotor with the secondary coil fixed on the rotating shaft. A gap is provided between the primary and secondary coils in order to make them entirely non-contact with each other. A soft magnetic material is used for these cores to make the magnetic reluctance small enough. Usually a sinusoidal AC electric energy is impressed on the primary coil and transmitted to the secondary coil instantaneously. Because of simple and sturdy structure of rotary transformer, it is utilized for various purposes such as: Steering Roll Connectors (SRC), Resolvers, Non-contact Torque Sensors and etc. Recently developments in resolver to digital techniques have made it possible to use resolver without any additional hardware. Utilizing microcomputer can help us to define shaft position alone with a software subroutine. An efficient control algorithm necessitates knowing accurate rotor's position without any noise. Rotary transformer has the advantages such as completely noiseless operation and infinite rotating life. To identify resolver's output voltages, knowing rotary transformer's model and estimating its parameters is necessary [1].

The equivalent circuit of axial flux rotary transformer is similar to that of radial flux rotary transformer which is shown in Fig. 2. Regarding to this figure the electrical equivalent circuit of rotary transformer is the same as that of conventional transformer [2]. So, the different parameters identification methods of conventional transformer can be used in axial flux rotary transformer, identically.



(a)

(b)

Fig. 1. (a) the structure of axial flux resolver and (b) the structure of axial flux rotary transformer

There are lots of works about the parameters estimation of transformer which are categorized in two groups: classic method and new ones which are using evolutionary algorithms, neural networks, finite element based methods and …. . In classic method, well known short circuit and no-load tests are carried out. Although these testes are simple, they have two major disadvantages: low accuracy and being time consuming.

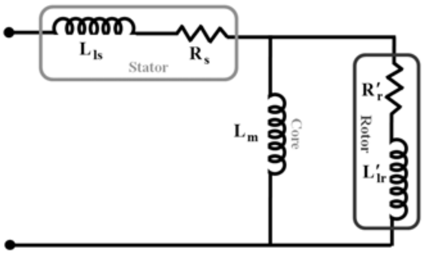


Fig. 2. The equivalent circuit of axial/radial flux rotary transformer in steady state

Similar to the radial flux rotary transformer [2], the equivalent circuit of rotary transformer in steady state is shown in Fig. 2. In this model core loss is omitted because nominal current level of RT is in 10^{-3} Ampere (mA) order. Note that, the secondary tap of rotary transformer (rotor) is shorted and its parameters are referred to primary (stator) side. Regarding Fig. 2, the equivalent circuit of rotary transformer is the same as that of induction motor [3-4]. Induction motor parameters identification methods which are using evolutionary algorithms [5-7], neural networks [8-9], d-q model, field calculation based methods [10-12] and DC-Pulse method [13-14] eliminate the disadvantages of classic method. These methods can be presumable in axial flux rotary transformers too [2]. The last method (DC pulse) which is based on a simple configuration has advantages of low cast, high accuracy and low test duration. This method estimates the machine's parameters based on analysis of charge or discharge stator current or both of them (average stator current) [13]. This method is used in this paper to estimate AFRT parameters. In DC-Pulse method the parameters are estimated by analyzing the stator current response to the DC-Pulse voltage, applied to the stator windings. An exponential regression is used in DC charge and discharge condition. Then, coefficients and time constants of signals are determined. Finally, the parameters of rotary transformer will be calculated according to the related equations and identified parameters which are validated by comparing these simulation results with experimental test results and 3-D time stepping finite element analysis.

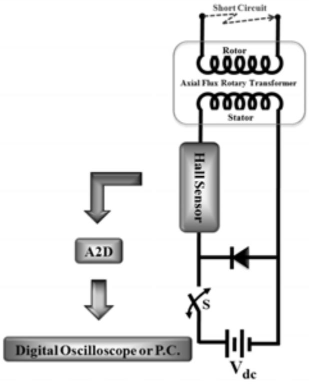


Fig. 3. Test set-up configuration

Parameters of Axial Flux Rotary Transformer Model

As regarded in Fig. 3, the stator winding of the rotary transformer is excited by a DC-Pulse voltage. When switch S is opened and closed, stator current (I_s) is sensed by Hall-Effect current sensor and its output voltage is delivered to the PC via an A/D card or monitored on digital oscilloscope. Finally, the stator current transfer function based on the circuit model of Fig. 2 can be obtained as follows [2]:

In charge:

(1-a) $$I_s(s)=\left|V_s\right| \cdot \frac{1}{r_{s1}} \cdot \frac{1+T_{r1}s}{1+(T_{r1}+T_{s1})s+(\sigma_1 T_{r1}T_{s1})s^2}$$

In discharge:

(1-b) $$I_s(s)=\left|V_s\right| \cdot \frac{L_{s2}}{{r_{s2}}^2} \cdot \frac{1+(\sigma_2 T_{r2})s}{1+(T_{r2}+T_{s2})s+(\sigma_2 T_{r2}T_{s2})s^2}$$

Applying inverse Laplace transformation to equation (1-a, b) stator current for charge and discharge condition in time domain will be written as:

(2-a) $$i_{s1}(t)=A_0(1+A_1 e^{-\frac{t}{T_1}}+A_2 e^{-\frac{t}{T_2}})$$

(2-b) $$i_{s2}(t)=B_0(B_1 e^{-\frac{t}{\tau_1}}+B_2 e^{-\frac{t}{\tau_2}})$$

where, A_1, A_2, B_1, B_2, T_1, T_2, τ_1 and τ_2 are coefficients and time constants which are defined using exponential regression. Based on equation (2–a, b) and these defined coefficients and time constants:

(3) $$T_{s1}=A_1(T_2-T_1)+T_2$$

(4) $$T_{r1}=T_1+T_2-T_{s1}$$

(5) $$\sigma_2=\frac{T_1T_2}{T_{r1}T_{s1}}$$

(6) $$T_{s2}=B_1\tau_1-B_2\tau_2$$

(7) $$T_{r2}=\tau_1+\tau_2-T_{s2}$$

(8) $$\sigma_2=\frac{\tau_1\tau_2}{T_{r2}T_{s2}}$$

The parameters of axial flux rotary transformer are:

(9) $$r_s=\frac{\left|V_s\right|}{2}(\frac{1}{A_0}+\frac{1}{B_0})$$

(10) $$L'_r=L_s=\frac{1}{2}(r_{s1}.T_{s1}+r_{s2}.T_{s2})$$

(11) $$L_m=\frac{1}{2}(L_{s1}\sqrt{1-\sigma_1}+L_{s2}\sqrt{1-\sigma_2})$$

(12) $$L'_{lr}=L_{ls}=L_s-L_m$$

(13) $$r'_r=\frac{1}{2}(\frac{L_{s1}}{T_{r1}}+\frac{L_{s2}}{T_{r2}})$$

where, r_s, r'_r are stator and rotor resistances, L'_{ls}, L'_{lr} are stator and rotor leakage inductances and L_m is mutual inductance between stator and rotor of AFRT. These identified parameters are used in the steady state and transient models of AFRT.

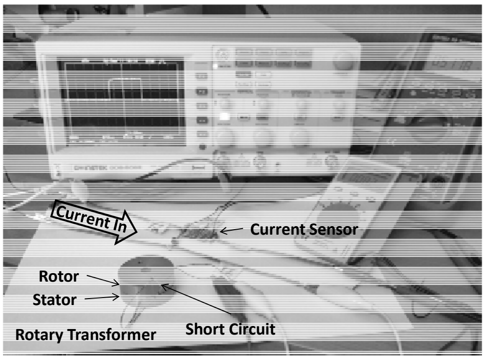


Fig. 4. The experimental AFRT and its test set-up configuration

Parameters Identification Experimental Set-up

In Figure 4 shows the experimental AFRT and its test set-up configuration. The DC voltage source of this set-up is chosen to provide rated current of AFRT.

Experimental recorded data of current curve, is shown in Fig. 5-a. It combines from two curves, charge, and discharge. These curves are fitted by exponential equations of (2-a, b) and are shown in fig. 5-b, c.

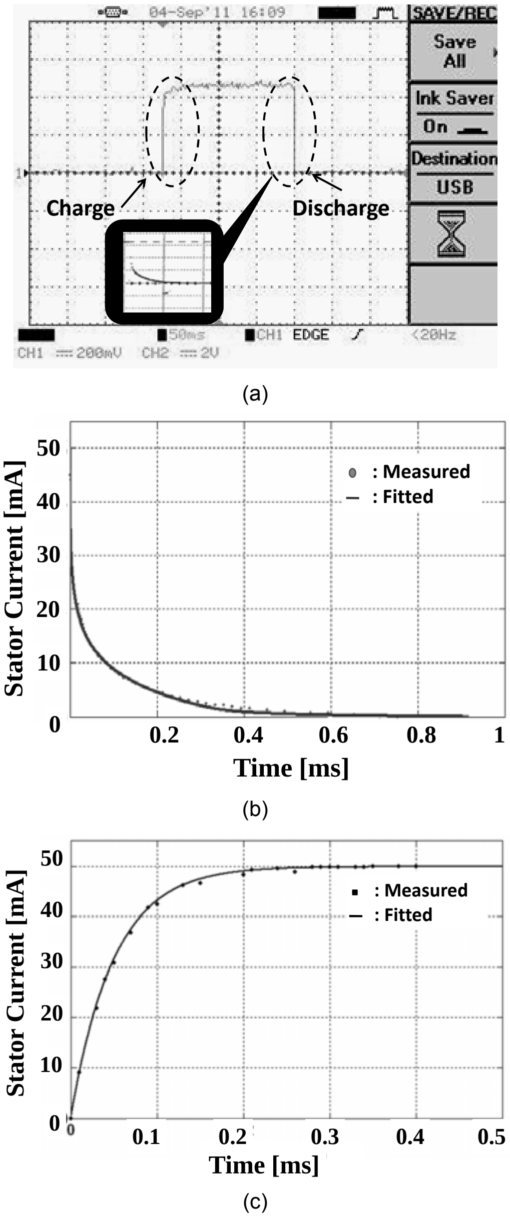


Fig. 5. (a) Current response (Sensor output on digital oscilloscope), (b) Discharge fitted Curve (c) Charge fitted Curve.

By curve fitting, coefficients and time constants of current equations can be obtained. Finally, using equations (9-13), the parameters were calculated. AFRT estimated parameters by using stator current analysis and classic methods are presented in table I & 2 respectively. These tables show that the identified R_s is equal in two classic and proposed method. Because, in these two methods R_s is obtained from DC test.

Table1: Estimated parameters based on Average DC-Pulse method

R_s [Ω]	R'_r [Ω]	L_m [H]	L'_{lr} [H]	L_{ls} [H]
15.95	5.49	0.0140	0.0024	0.0026

Table 2: Estimated parameters based on classic method

R_s [Ω]	R'_r [Ω]	L_m [H]	L'_{lr} [H]	L_{ls} [H]
15.95	5.1	0.0134	0.0022	0.0027

AFRT Performance Prediction

Performance of AFRT can be predicted by two methods: A) Solving differential equations of AFRT equivalent circuit analytically in Matlab/Simulink environment, B) Numerical solving of Maxwell partial differential equations (PDEs) using time stepping finite element method (TS-FEM). In first analytic method, AFRT equivalent circuit with identified parameters is simulated in particular time period. But in second one, Maxwell equations are solved on the AFRT geometry independent of identified parameters. First method is the most time saving method in comparison with FEM and experimental method. If estimated parameters and analytic simulation results are confirmed by 3D-FEM and experimental ones, the performance of AFRT could be predicted easily and quickly by first method as accurate as TS-3D FEM and experimental methods.

A. Analytic Model of AFRT

Like conventional transformers, AFRT analytic model can be obtained by using voltage-current and flux linkage-current equations [16]. In AFRT the secondary winding can rotate. But, because of symmetric topology of AFRT (Fig. 1-(b)) causes that rotating secondary winding does not affect on its electrical performance. Therefore, by using estimated parameters and analytic model AFRT's performance was studied. In order to evaluate the accuracy of proposed parameter identification method, load test was performed. In this test, rotary transformer was excited by rated voltage and frequency with a resistive load (R_L = 156 Ω to load the AFRT in Rated current). Figure 6 shows experimental stator current compared with simulation result based on estimated parameters (presented in table 1).

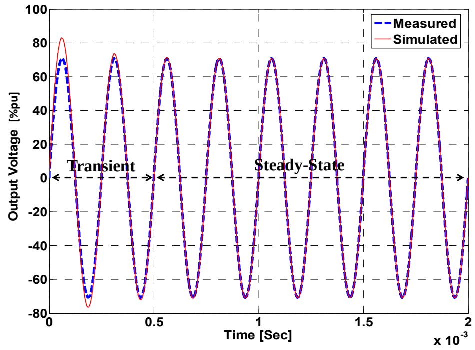


Fig. 6. Comparing load test response using estimated parameters from proposed method and experimental test

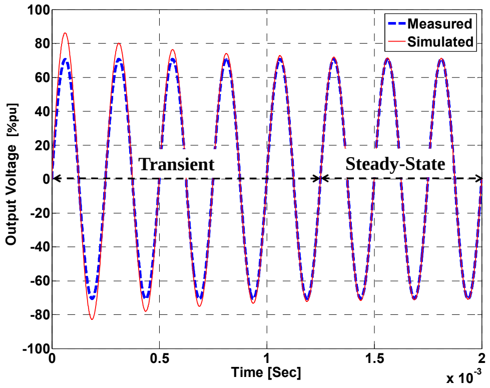
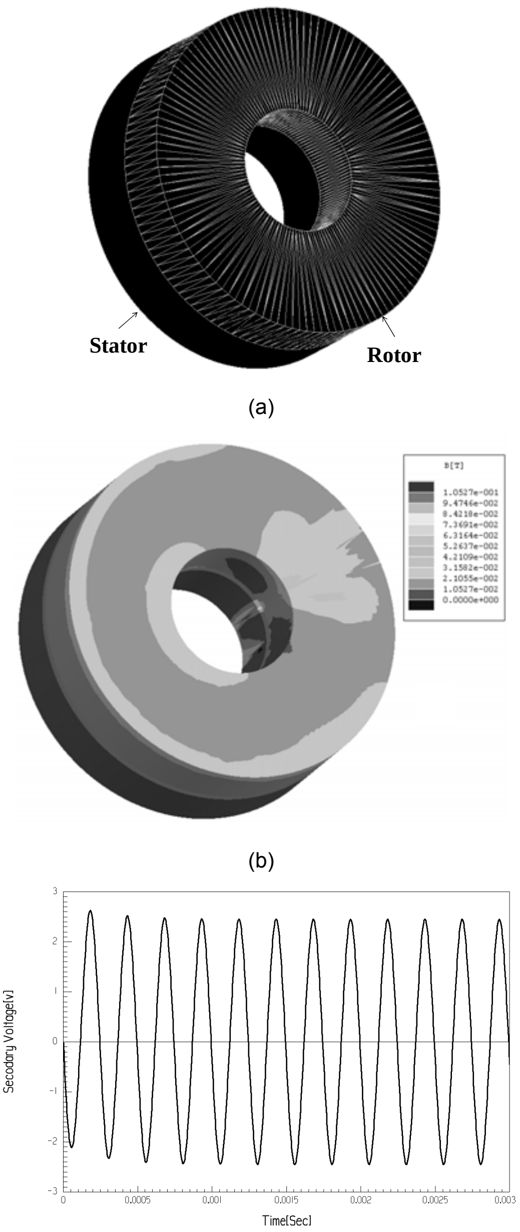


Fig. 7. Comparing load test response using estimated parameters from classic method and experimental test

Also, Fig. 7 shows similar comparison with experimental result and simulated one, based on the parameters calculated by classic method (presented in table 2). As appeared in the Fig. 6 the difference between calculated and measured transient time (which are related to R'_r and L_m [17]) is more accurate than that is in Fig. 7, the curves in Fig. 6 are similar than the curves in fig. 7. Precise comparison will be done after 3D-FEM simulation.



(a)

(b)

(c)

Fig. 8. 3D FE Analysis of AFRT (a) Making mesh on the surface of AFRT (b) magnetic flux density distribution on the surface of AFRT (c) Secondary output voltage

B. Finite Element Analysis

In the next step, time stepping finite element analysis is used to validate the DC-Pulse results. Because, there is not any symmetric two dimensional cross-section in the AFRT topology, the field calculation has to be done in three dimensional (3D) spaces. Also, transmitted power between rotor and stator of AFRT is very low (about several milli-watt) therefore, the iron core of AFRT generally is constructed solid. So, it is essential to consider the effect of eddy current in performance prediction by using a complex transient solution.

Table 3 shows the design parameters of studied AFRT. Using these parameters, the schematic of AFRT is drawn in FE software environment. After assigning materials, boundary conditions, excitation source and making mesh, the problem is solved to calculate the performance of AFRT. Figure 8 shows mesh, magnetic flux density and secondary voltage (at rated current) of simulated AFRT respectively. The maximum Flux density of 0.1 T indicates that no saturation occurs even at rated current.

Table 3: The parameters of studied AFRT

Parameter	Value	Unit
Max. Output power	15	mw
Frequency	4000	Hz
Rated Voltage	10	V_{pp}
Rated Current	10	mA
Air gap length	1	mm
Core outer /inner diameters	72/52	mm
Core length, stator/rotor	10	mm
Number of turns, Stator/Rotor	200	-

Validation of AFRT Identified Parameters

In order to validate AFRT estimated parameters, simulation results of analytic and TS-3D FE analysis must be compared with experimental ones. If the comparison results are satisfactory it can be concluded that the proposed method be able to substitute with FE and experimental method to save time of test.

The parameters of classic and proposed methods (Tables 1, 2) are used in Matlab/Simulink model of AFRT to give the simulation results (Figs. 6, 7). 3D time stepping FEM and practical test are employed to evaluate the current waveform of AFRT, too. These current wave forms are presented in Fig. 9. These currents are normalized with nominal current. This figure shows that the simulation results based on estimated parameters (by average DC pulse method) follow the experimental and FEM results.

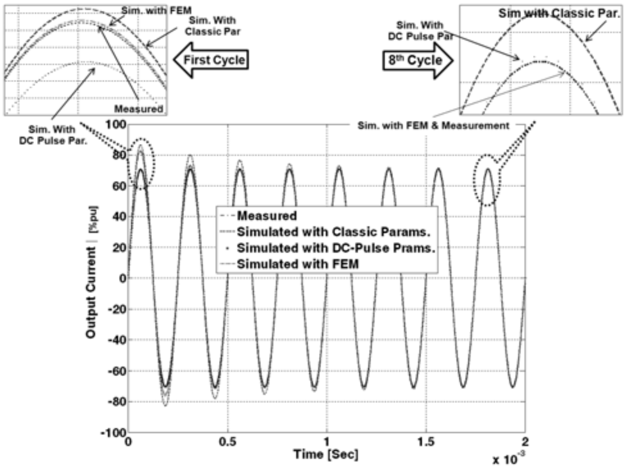


Fig. 9. The comparison of normalized output current waveform in resistive load test of AFRT using different parameter estimation methods: "-" simulation regarding classic method parameters, "**.**" simulation results based on DC-Pulse parameters, "--" the result of 3-D FEM and "-." experimental results

Table 4. The comparison of the amplitude of stator current in the transient and steady state based on different parameter estimation methods

	Measured	SIMULATED WITH 3-D FEM	Simulated with Classic Method	Simulated with Average DC-Pulse Method
Normalized Steady-State Amplitude [% pu]	70.75	70.73	71.18	70.78
Normalized Transient Amplitude [%pu]	82.12	82.49	86.32	78.91

The exact comparison is performed based on the amplitude of stator current in the transient and steady state. Table 4 and bar chart of Fig. 10 shows this comparison results. Also, the absolute error of all simulating methods with experimental results are shown in Fig. 11.

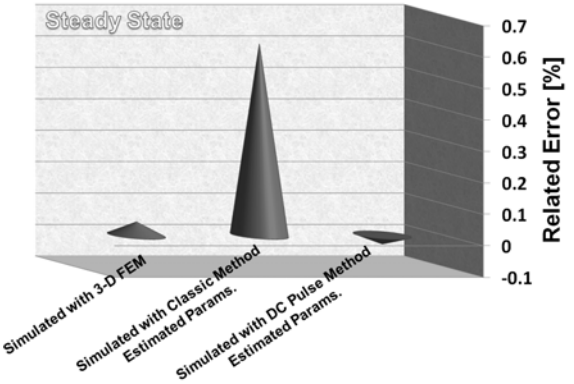


Fig. 10. Related error of simulation with classic, 3D FE and DC pulse parameter estimation methods with experimental results (In Steady State)

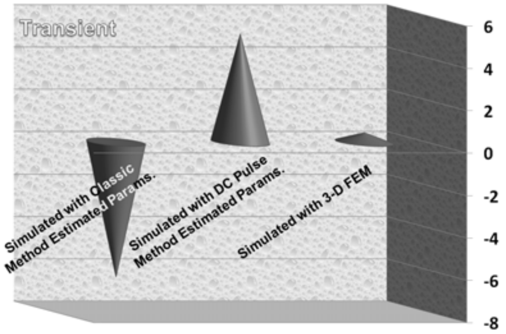


Fig. 11. Related error of simulation with classic, 3D FE and DC pulse parameter estimation methods with experimental results (In Transient)

Table 4, Figs. 10 and Fig. 11 show that in both steady state and transient conditions, the parameters of average DC-Pulse method are more accurate than those of classic method. These results validate the proposed method and indicate that the average DC-Pulse method, not only is fast and simple, but also is more accurate than classic one.

This parameter identification method can be used to estimate the AFR parameters with small modification. When all AFRT and AFR parameters were found, it will be possible to predict the effect of some faults (such as static and dynamic eccentricity, short circuit condition …) on detected position. Also, estimated parameters used to define the eigen values of AFR and its state matrix in space state which will be detailed in an upcoming paper.

Conclusions

It is observed that the proposed analysis of stator average DC charge and discharge current of an axial flux rotary transformer (AFRT) could identify its parameters. In comparison with other parameters estimation methods such as classic method, FEM, … the proposed method is accurate, time saving and low cost (needs a very simple test set-up). These advantages lead the authors to suggest this method to use in product lines of high precision resolver factories. In addition, simulation of AFRT based on parameters identified with proposed method indicates that in steady state the results are similar to experimental and time stepping 3D-FEM simulation results. Because of using the estimated parameters in steady state equivalent circuit of AFRT, this investigation shows that in transient condition, the simulation results are not accurate enough. Also, it was determined that 3D FEM was very accurate but, it was more time consuming than other procedures. Finally, this study confirms that parameters which are identified by proposed average DC pulse method are accurate enough to use in AFRT simulation instead of FE method.

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