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Determination of Combination of Input Values of Simulated Motor Using Taguchi Method

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Abstract:- The most popular type of motors in use today is squirrel-cage induction motors. All types of motor faults can be studied if a motor could be simulated based on the motor without faults. The goal of this study was to determine the input optimum values for making it almost identical values of outputs f the simulated motor to the target values on the nameplate data of the actual motor. In this study, the Taguchi method, calculated using MATLAB, was used to optimize the values input of the simulated motors. For dynamic simulation purposes, inputs and outputs of a simulated motor need to be selected. In this study, stator resistance, stator inductance, rotor bar resistance, rotor bar inductance, rotor end ring resistance, and rotor end ring were selected as the input parameters. Rotations per minute (rpm), torque, and stator current were selected as output parameters; they are also provided on the nameplate data on the actual motor. These results allow us to develop dynamic simulations to study a variety of motor faults and to compare the results of a simulated motor with and without faults, to better understand and analyze the frequency domain, determine the root cause of the vibrations. All code work is shown in the paper and one new formula was developed based on this study.

Keywords:- *Model, Simulation, Optimization, Modelling, Dynamic Simulation, MATLAB.*

I. INTRODUCTION

Squirrel induction motors are used mainly in industry. Experiments on motors, conducted in a laboratory setting, are expensive and limited, because the motor should be broken to create the fault to be studied. Another motor is again needed to be broken to study a different fault. Large capacity motors are generally not allowed to break because of cost and safety factors. However, conducting research on a simulated motor, with and without faults, saves an enormous amount of time and money. Motors of any capacity, with any type of fault can be studied if a motor could be simulated in Simulink MATLAB or other software. In the present study, an actual motor without a fault needed to be simulated. After developing a dynamic simulation, several types of motor faults were studied, based on the simulated motor without faults. It is necessary to adequately know the electric, magnetic, and mechanical behavior of motors without faults for a reliable diagnostic method of fault identification.

For dynamic simulation purposes, it is important to know first, that the output parameters of a simulated motor and a actual motor are the same. Rotational speed (rpm), torque, and stator current are selected as output parameters of a simulated motor because these parameters are given on the nameplate data on the motor. The parameters on the nameplate of a motor become the parameters to check output parameters of a simulated motor, correct or not. Output parameters from a simulated model should be very close to the nameplate data on the actual motor if the model is robust. In this study, the parameters on the nameplate of the motor are called the targets and outputs of the simulated model developed in Simulink MATLAB are called the output parameters.

An actual motor with 11 kW and 415V is studied in this research work. All the parameters of a normally-functioning actual motor are given in Appendix 1. Inputs of the dynamic simulation model are classified into three categories: 1) parameters on the nameplate from the manufacturer; 2) calculated parameters from the material and the actual dimensions of the motor; and 3) measured parameters in the laboratory. Some parameters such as the number of stator coils/pole/phase, resistances and inductances of stator and rotor bars and so on are calculated and/or measured experimentally if not supplied by the manufacturers.

1. Data on the nameplate from the manufacturer: nominal voltage [V], nominal torque [Hm], nominal current [A], number of poles, rotational speed [rpm], frequency [Hz], Δ/Y connection, efficiency, power factor, number of stator coils/poles/phases.
2. Calculated data: number of turns in the stator coils, air gap average length [m], synchronous speed [rpm], slip [%], rotor angular velocity [rps], rotor mechanical speed [hz], rotor frequency [hz], stator slot pitch [rad], pole pitch [rad], number of stator coils/pole/phase, number of turns in the stator.
3. Data from the laboratory: stator layout, number of rotor bars, number of stator slots, stator slot pitch [slots], rotor stack length [m], average radius [m], stator resistance [ohm], stator leakage inductance [H], rotor bar resistance [ohm], rotor bar inductance [H], rotor end ring resistance [ohm], rotor end ring inductance [H].

Six parameters such as stator resistance; stator inductance; rotor bar resistance; rotor bar inductance; rotor end ring resistance; and rotor end ring inductance from the input parameters of a simulated motor, are selected as input parameters, because these parameters are the most influential factors that affect the output parameters. In order to understand key frequencies of motors with and without faults, the electrical, mechanical, and electromagnetic behaviors of induction motors need to be understood. The dynamic simulation model with highly accurate inputs models the same the actual motor in the lab or field. Therefore, the goal of this paper is to find the optimum input parameters that make the minimum difference between outputs and targets, as evaluated by the Taguchi method.

II. INPUT PARAMETER OPTIMIZATION

The Taguchi method is a systematic application of the design and analysis of experiments for the purpose of designing and improving product quality [1]. There are three types of Taguchi loss functions: 1) "the nominal the best; "the smaller the better;" and "the larger the better." The quality characteristic "the nominal best," occurs whenever the output 'y' has a finite target value, usually nonzero, and the quality loss is symmetric on the either side of the target. The nominal the best of the Taguchi loss function is going to be used in this study because the targets, such as the nameplate parameters, are clear. So, this particular loss function will be used to optimise the input parameters to make the minimum difference between outputs and targets and to improve the shape time domain of output parameters of the dynamic simulation model of a squirrel-cage induction motor that has been developed by Purvee [2].

The input parameters are listed in Table I. These six parameters were selected because they have the greatest influence on the motor outputs compared to other input parameters. In addition, these parameters were selected because they are capable of being varied within +/-10%, while still obtaining outputs that are almost at the value of the targets.

TABLE I
INPUT PARAMETERS

Input parameter	**Notation**	**Experimental levels**		
		1 (-10%)	**2**	**3 (10%)**
Resistance of stator	Rs	Rs-0. 1*Rs	Rs	Rs+0. 1*Rs
Resistance of rotor bar	Rb	Rb-0.1*Rb	Rb	Rb+0. 1*Rb
Resistance of rotor end-ring	Re	Re-0.1Re	Re	Re+0.1Re
Inductance of stator	Ls	Ll_s-0. 1*Ll_s	Ll_s	Ll_s+0.1*Ll_s
Inductance of rotor bar	Lb	Ll_b-0. 1*Ll_b	Ll_b	Ll_b+0.1*Ll_b
Inductance of end ring	Le	Ll_e-0. 1*L_e	Ll_e	Ll_e+0.1*Ll_e

The values of input parameters of resistance of stator, resistance of rotor bar, resistance of rotor end-ring, inductance of stator, inductance of rotor bar, inductance of end ring are listed in Table II.

TABLE II
VALUES OF INPUT PARAMETERS

Notation	**Rotational speed (RPM)**			**Torque (Te)**			**Stator current (Is)**		
	1 (-10%)	**2**	**3 (10%)**	**1 (-10%)**	**2**	**3 (10%)**	**1 (-10%)**	**2**	**3 (10%)**
Rs	2.35	2.608454802	2.87	3.58	3.98	4.37	4.05	4.50	4.95
Rb	1.59703E-05	1.77448E-05	1.95193E-05	3.64E-05	3.31.E-05	3.6E-05	7.3E-05	6.67.E-05	7.3E-05
Re	1.37214E-06	1.5246E-06	1.67706E-06	1.51E-06	1.37.E-06	1.5E-06	3.4E-06	3.10.E-06	3.4E-06
Ls	0.01458	0.0162	0.01782	0.02178	1.98.E-02	0.02178	0.0033	3.00.E-03	0.0033
Lb	1.73696E-06	1.92995E-06	2.12295E-06	1.93E-06	1.75.E-06	1.9E-06	4.9E-07	4.44.E-07	4.9E-07
Le	1.3704E-07	1.52266E-07	1.67493E-07	1.14E-07	1.04.E-07	1.1E-07	2.4E-07	2.22.E-07	2.4E-07

An efficient way to optimize the input parameters simultaneously is to plan experiments using L_{18} orthogonal arrays [1]. Code to distribute the six input parameters within the L18 orthogonal array was developed specifically for this project by the author [2] and the results are shown in Table III.

TABLE III

EXPERIMENTAL DISTRIBUTION OF INPUT PARAMETERS WITHIN THE ORTHOGONAL ARRAY (RPM only)

Input parameters					
Rs	**Rb**	**Re**	**Lls**	**Llb**	**Lle**
2.35	1.597.E-05	1.372.E-06	1.458.E-02	1.737.E-06	1.370.E-07
2.35	1.774.E-05	1.525.E-06	1.620.E-02	1.930.E-06	1.523.E-07
2.35	1.952.E-05	1.677.E-06	1.782.E-02	2.123.E-06	1.675.E-07
2.61	1.597.E-05	1.372.E-06	1.620.E-02	1.930.E-06	1.675.E-07
2.61	1.774.E-05	1.525.E-06	1.782.E-02	2.123.E-06	1.370.E-07
2.61	1.952.E-05	1.677.E-06	1.458.E-02	1.737.E-06	1.523.E-07
2.87	1.597.E-05	1.525.E-06	1.458.E-02	2.123.E-06	1.675.E-07
2.87	1.774.E-05	1.677.E-06	1.620.E-02	1.737.E-06	1.370.E-07
2.87	1.952.E-05	1.372.E-06	1.782.E-02	1.930.E-06	1.523.E-07
2.35	1.597.E-05	1.677.E-06	1.782.E-02	1.930.E-06	1.370.E-07
2.35	1.774.E-05	1.372.E-06	1.458.E-02	2.123.E-06	1.523.E-07
2.35	1.952.E-05	1.525.E-06	1.620.E-02	1.737.E-06	1.675.E-07
2.61	1.597.E-05	1.525.E-06	1.782.E-02	1.737.E-06	1.523.E-07
2.61	1.774.E-05	1.677.E-06	1.458.E-02	1.930.E-06	1.675.E-07
2.61	1.952.E-05	1.372.E-06	1.620.E-02	2.123.E-06	1.370.E-07
2.87	1.597.E-05	1.677.E-06	1.620.E-02	2.123.E-06	1.523.E-07
2.87	1.774.E-05	1.372.E-06	1.782.E-02	1.737.E-06	1.675.E-07
2.87	1.952.E-05	1.525.E-06	1.458.E-02	1.930.E-06	1.370.E-07

The most influential six input parameters of RPM are determined by values in each row. 18 rows mean 18 experiments. These 18 experiments are repeated until the minimum differences are achieved between the output parameters of the model, and the target (parameters on the nameplate of the motors). This is the same processes of the torque (Te), the stator current (Is). The final best results of targets such as torque, rotational speed, and stator are shown Table IV.

TABLE IV

OUTPUT PARAMETERS

№	**RPM**	**Te**	**Is**	**№**	**RPM**	**Te**	**Is**
	1450	73.69	20.8		1450	73.69	20.8
1	1452.133	74.615	20.228	10	1449.512	74.302	20.768
2	1449.811	74.337	20.644	11	1451.055	74.483	20.529
3	1447.175	74.008	21.123	12	1448.834	74.223	20.639
4	1449.839	74.312	20.991	13	1448.580	74.166	21.060
5	1447.344	74.010	21.311	14	1448.623	74.204	20.879
6	1447.737	74.106	20.761	15	1447.788	74.067	21.101
7	1448.524	74.159	21.318	16	1447.117	73.987	21.522
8	1446.365	73.916	21.246	17	1446.335	73.858	21.573
9	1445.179	73.726	21.696	18	1446.672	73.951	21.172

The 18 output values obtained experimentally were used to generate 'the nominal the best' loss function using [3] and [4].

The analysis of variance (ANOVA) method was used to determine the percentage contribution of each of the parameters studied; we used this method to quantitatively estimate the input that the parameters made to the overall outputs, expressed as a percentage, as described previously [1] - [5]. The fundamental techniques of ANOVA involve the total sum of squares, the variance ratio, and degrees of freedom.

To simplify the analysis, code was developed that generated 'the nominal the best,' (S/N) ratios, and sum of squares [6].

The S/N ratio and values for the sums of the squares of, outputs (are torque, rotations per minute, stator current), are tabulated in Table V.

TABLE V
OUTPUT PARAMETERS, S/N RATIO AND SUMS OF SQUARES VALUES (RESULTS OF GENERATE NOMINAL BEST)

№	Outputs			Nominal the best eta			S/N ratios SN			Squares of S/N ratio sqSN			Squares to mean m		
	RPM	**Te**	**Is**	**RPM**	**Te**	**Is**	**RPM**	**Te**	**Is**	**RPM**	**Te**	**Is**	**RPM**	**Te**	**Is**
1	1452.13	74.62	20.23	4.55	0.86	0.33	-6.58	0.68	4.85	43.29	0.46	23.52	7.74	62.61	44.76
2	1449.81	74.34	20.64	0.04	0.42	0.02	14.45	3.78	16.14	208.81	14.26	260.47	332.99	23.16	21.15
3	1447.17	74.01	21.12	7.98	0.10	0.10	-9.02	9.95	9.82	81.39	99.03	96.45	27.29	1.85	2.96
4	1449.84	74.31	20.99	0.03	0.39	0.04	15.84	4.12	14.36	250.94	16.99	206.27	385.68	19.96	7.97
5	1447.34	74.01	21.31	7.05	0.10	0.26	-8.48	9.90	5.84	71.97	98.06	34.08	21.96	1.72	32.51
6	1447.74	74.11	20.76	5.12	0.17	0.00	-7.09	7.63	28.11	50.30	58.15	790.44	10.85	0.93	274.73
7	1448.52	74.16	21.32	2.18	0.22	0.27	-3.38	6.58	5.71	11.43	43.25	32.62	0.17	4.05	33.98
8	1446.36	73.92	21.25	13.21	0.05	0.20	-11.21	12.91	7.02	125.67	166.57	49.30	54.95	18.64	20.41
9	1445.18	73.73	21.70	23.24	0.00	0.80	-13.66	28.92	0.95	186.65	836.57	0.91	97.31	413.5	112.12
10	1449.51	74.30	20.77	0.24	0.37	0.00	6.22	4.27	29.79	38.72	18.23	887.63	100.41	18.66	333.18
11	1451.05	74.48	20.53	1.11	0.63	0.07	-0.46	2.01	11.34	0.21	4.04	128.64	11.13	43.28	0.04
12	1448.83	74.22	20.64	1.36	0.28	0.03	-1.34	5.47	15.89	1.78	29.91	252.44	6.06	9.73	18.91
13	1448.58	74.17	21.06	2.02	0.23	0.07	-3.05	6.45	11.70	9.29	41.60	136.88	0.56	4.58	0.03
14	1448.62	74.20	20.88	1.90	0.26	0.01	-2.78	5.79	22.10	7.72	33.50	488.27	1.04	7.85	111.45
15	1447.79	74.07	21.10	4.89	0.14	0.09	-6.89	8.46	10.43	47.54	71.63	108.71	9.59	0.02	1.24
16	1447.12	73.99	21.52	8.31	0.09	0.52	-9.20	10.55	2.83	84.58	111.23	8.01	29.15	3.83	75.86
17	1446.34	73.86	21.57	13.43	0.03	0.60	-11.28	15.50	2.23	127.25	240.21	4.98	55.99	47.74	86.63
18	1446.67	73.95	21.17	11.08	0.07	0.14	-10.44	11.65	8.60	109.08	135.74	73.96	44.18	9.37	8.64
	Average			Average			Average			Grand total sum of squares			Total sum of squares to mean		
	1448.26	74.14	21.03	5.98	0.25	0.20	-3.80	8.59	11.54	1456.64	2019.4	3583.5	1197.06	691.47	1186.6

The evaluated S/N ratios $\left(\eta_{S/Nij}\right)$ are determined by the S/N ratios that were calculated using values produced from the experimental distributions (see Table III). The evaluated S/N ratio is calculated by (1), which was developed based on this research study.

$$\eta_{S/Nij} = \frac{\sum_{i=1}^{n} \eta_{S/Nirj}}{n_k} \tag{1}$$

Here: $\eta_{S/Nirj}$ − sum of the S/N ratio in the particular column, n_k − number of non-zero values of the S/N ratio.

The following four steps are used to calculate the evaluated S/N ratios:

Step 1. Distribution of 1s, 2s, and 3s into orthogonal arrays: The R_s, R_b, R_e, L_s, L_b, L_e columns of of orthogonal arrays kept in orth18.txt have been divided into three columns each, matching the three experimental levels. For example: the Column R_s is divided into columns labeled R_{s1}, R_{s2} and R_{s3}. All 1s are in R_{s1}, all 2s are in R_{s2}, & all 3s are in R_{s3}. All the rest of the parameters follow this same process.
Step 2. Replacement by S/N ratio: All 1s in R_{s1}, R_{b1}, R_{e1},L_{s1},L_{b1},L_{e1}, and all 2s in R_{s2}, R_{b2}, R_{e2}, L_{s2}, L_{b2}, L_{e2} and all threes in R_{s3}, R_{b3}, R_{e3}, L_{s3}, L_{b3}, L_{e3} were replaced by the S/N ratios of rotational speed, torque and stator current corresponding to the experimental distribution of the row inTable V. The evaluated S/N ratio is calculated by (1).
Step 3. Reconstruct a table: The evaluated S/N ratios of RPM are reconstructed into the table with six rows and three columns.
Step 4. Plot a Taguchi graph: Taguchi graphs are plotted by the evaluated S/N ratios of each parameter (each row).

The evaluated S/N ratios of torque, stator current are calculated the same way as the evaluated S/N ratios of rotational speed.

Codes for Steps 1 - 4 were developed by the author [7] and the results are shown in Tables VII-IX.

TABLE VII
DISTRIBUTION OF ORTHOGONAL ARRAYS

Input parameters						**Distribution of input parameters**																	
R			**L**			**Rs**			**Rb**			**Re**			**Ls**			**Lb**			**Le**		
s	b	e	s	b	e	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	1	1	1	1	1	1			1			1			1			1			1		
1	2	2	2	2	2	1				2			2			2			2			2	
1	3	3	3	3	3	1					3			3			3			3			3
2	1	1	2	2	3		2		1			1				2			2				3
2	2	2	3	3	1		2			2			2				3			3	1		
2	3	3	1	1	2		2				3			3	1			1				2	
3	1	2	1	3	3			3	1				2		1					3			3
3	2	3	2	1	1			3		2				3		2		1			1		
3	3	1	3	2	2			3			3	1					3		2			2	
1	1	3	3	2	1	1			1					3			3		2		1		
1	2	1	1	3	2	1				2		1			1					3		2	
1	3	2	2	1	3	1					3		2			2		1					3
2	1	2	3	1	2		2		1				2				3	1				2	
2	2	3	1	2	3		2			2				3	1				2				3
2	3	1	2	3	1		2				3	1				2				3	1		
3	1	3	2	3	2			3	1					3		2				3		2	
3	2	1	3	1	3			3		2		1					3	1					3
3	3	2	1	2	1			3			3		2		1				2		1		

Based on Table VII the results of the evaluated S/N ratios of rotational speed (RPM), torque (Te) and stator current (Is) were calculated and are shown in Table VIII.

TABLE VIII
DISTRIBUTION OF S/N RATIO AND S/N RATIOS

S/N	**Rs1**	**Rs2**	**Rs3**	**Rb1**	**Rb2**	**Rb3**	**Re1**	**Re2**	**Re3**	**Ls1**	**Ls2**	**Ls3**	**Lb1**	**Lb2**	**Lb3**	**Le1**	**Le2**	**Le3**
Rotational Speed (RPM)																		
-6.6	-6.6			-6.6			-6.6			-6.6			-6.6			-6.6		
14.5	14.5				14.5			14.5			14.5			14.5			14.5	
-9.2	-9.2					-9.2			-9.2			-9.2			-9.2			-9.2
15.8		15.8		15.8			15.8				15.8			15.8				15.8
-8.5		-8.5			-8.5			-8.5				-8.5			-8.5	-8.5		
-7.9		-7.9				-7.9			-7.9	-7.9			-7.9				-7.9	

-3.4			-3.4	-3.4				-3.4		-3.4					-3.4			-3.4
-11.2			-11.2		-11.2				-11.2		-11.2		-11.2			-11.2		
-13.7			-13.7			-13.7	-13.7					-13.7		-13.7			-13.7	
6.2	6.2			6.2					6.2			6.2		6.2		6.2		
-0.5	-0.5				-0.5		-0.5			-0.5					-0.5		-0.5	
-1.3	-1.3					-1.3		-1.3			-1.3		-1.3					-1.3
-3.5		-3.5		-3.5				-3.5				-3.5	-3.5				-3.5	
-2.8		-2.8			-2.8				-2.8	-2.8				-2.8				-2.8
-6.9		-6.9				-6.9	-6.9				-6.9				-6.9	-6.9		
-9.2			-9.2	-9.2					-9.2		-9.2				-9.2		-9.2	
-11.3			-11.3		-11.3		-11.3					-11.3	-11.3					-11.3
-1.4			-1.4			-1.4		-1.4		-1.4				-1.4		-1.4		
Evaluated	**0.5**	**-2.1**	**-9.9**	**0.0**	**-3.3**	**-8.1**	**-3.8**	**-2.0**	**-5.5**	**-5.1**	**0.3**	**-6.5**	**-6.8**	**1.6**	**-6.2**	**-6.2**	**-3.2**	**-2.0**
Torque (Te)																		
0.7	0.7			0.7			0.7			0.7			0.7			0.7		
3.8	3.8				3.8			3.8			3.8			3.8			3.8	
10.0	10.0					10.0			10.0			10.0			10.0			10.0
4.1		4.1		4.1			4.1				4.1			4.1				4.1
9.9		9.9			9.9			9.9				9.9			9.9	9.9		
7.6		7.6				7.6			7.6	7.6			7.6				7.6	
6.6			6.6	6.6				6.6		6.6					6.6			6.6
12.9			12.9		12.9				12.9		12.9		12.9			12.9		
28.9			28.9			28.9	28.9					28.9		28.9			28.9	
4.3	4.3			4.3					4.3			4.3		4.3		4.3		
2.0	2.0				2.0		2.0			2.0					2.0		2.0	
5.5	5.5					5.5		5.5			5.5		5.5					5.5
6.4		6.4		6.4				6.4				6.4	6.4				6.4	
5.8		5.8			5.8				5.8	5.8				5.8				5.8
8.5		8.5				8.5	8.5				8.5				8.5	8.5		
10.5			10.5	10.5					10.5		10.5				10.5		10.5	
15.5			15.5		15.5		15.5					15.5	15.5					15.5
11.7	0.0		11.7			11.7		11.7		11.7				11.7		11.7		
Evaluated	**4.4**	**7.1**	**14.4**	**5.4**	**8.3**	**12.0**	**9.9**	**7.3**	**8.5**	**5.7**	**7.5**	**12.5**	**8.1**	**9.8**	**7.9**	**8.0**	**9.9**	**7.9**
Stator current (Is)																		
4.8	4.8			4.8			4.8			4.8			4.8			4.8		
16.1	16.1				16.1			16.1			16.1			16.1			16.1	

9.8	9.8					9.8			9.8			9.8			9.8			9.8
14.4		14.4		14.4			14.4				14.4			14.4				14.4
5.8		5.8			5.8			5.8				5.8			5.8	5.8		
28.1		28.1				28.1			28.1	28.1			28.1				28.1	
5.7			5.7	5.7				5.7		5.7					5.7			5.7
7.0			7.0		7.0				7.0		7.0		7.0			7.0		
1.0			1.0			1.0	1.0					1.0		1.0			1.0	
29.8	29.8			29.8					29.8			29.8		29.8		29.8		
11.3	11.3				11.3		11.3			11.3					11.3		11.3	
15.9	15.9					15.9		15.9			15.9		15.9					15.9
11.7		11.7		11.7				11.7				11.7	11.7				11.7	
22.1		22.1			22.1				22.1	22.1				22.1				22.1
10.4		10.4				10.4	10.4				10.4				10.4	10.4		
2.8			2.8	2.8					2.8		2.8				2.8		2.8	
2.2			2.2		2.2		2.2					2.2	2.2					2.2
8.6			8.6			8.6		8.6		8.6				8.6		8.6		
Evaluated	**14.6**	**15.4**	**4.6**	**11.5**	**10.8**	**12.3**	**7.4**	**10.6**	**16.6**	**13.5**	**11.1**	**10.1**	**11.6**	**15.3**	**7.7**	**11.1**	**11.8**	**11.7**

The evaluated S/N ratios of rotational speed, stator current and torque among all levels can be determined by using the values from the final row in Table VIII. The evaluated S/N ratios and calculated values are shown in Table IX.

TABLE IX
THE EVALUATED S/N RATIOS AND CALCULATED VALUES

Parameter	**Evaluated S/N ratios at experimental levels (*L*)**			**Degrees of Freedom (DOFr)**	**Sum of Squares (SS_S/Nij)**	**Mean square (Msq)**	**Variance ratio Fr**	**% of variance ratio Fr**	**Error of mean square (eMsq)**
	1	**2**	**3**						
Rotation per minute (rpm)									
Rss	0.546	-2.076	-9.862	2	351.680	175.840	6.460	29.379	
Rb	-0.024	-3.294	-8.075	2	196.756	98.378	3.614	16.437	
Re	-3.839	-2.040	-5.513	2	36.192	18.096	0.665	3.023	27.218
Lls	-5.123	0.276	-6.545	2	155.396	77.698	2.855	12.981	
Llb	-6.757	1.605	-6.240	2	263.476	131.738	4.840	22.010	
Lle	-6.232	-3.168	-1.993	2	57.469	28.734	1.056	4.801	
Torque (Te)									
Rss	4.359	7.058	14.350	2	320.576	160.288	18.062	46.361	
Rb	5.440	8.314	12.014	2	130.331	65.165	7.343	18.848	
Re	9.949	7.304	8.514	2	21.037	10.518	1.185	3.042	8.874
Lls	5.721	7.547	12.499	2	147.594	73.797	8.316	21.345	
Llb	8.104	9.755	7.908	2	12.347	6.174	0.696	1.786	
Lle	7.978	9.889	7.901	2	15.216	7.608	0.857	2.201	
Stator current (Is)									
Rss	14.639	15.423	4.558	2	440.587	220.294	4.226	37.132	
Rb	11.541	10.778	12.300	2	6.949	3.475	0.067	0.586	
Re	7.361	10.646	16.613	2	264.002	132.001	2.532	22.250	52.123
Lls	13.452	11.111	10.056	2	36.263	18.131	0.348	3.056	
Llb	11.634	15.324	7.661	2	176.220	88.110	1.690	14.851	
Lle	11.088	11.846	11.685	2	1.914	0.957	0.018	0.161	

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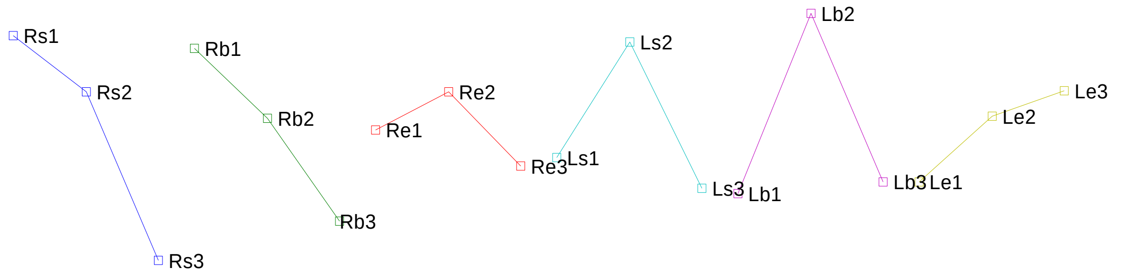
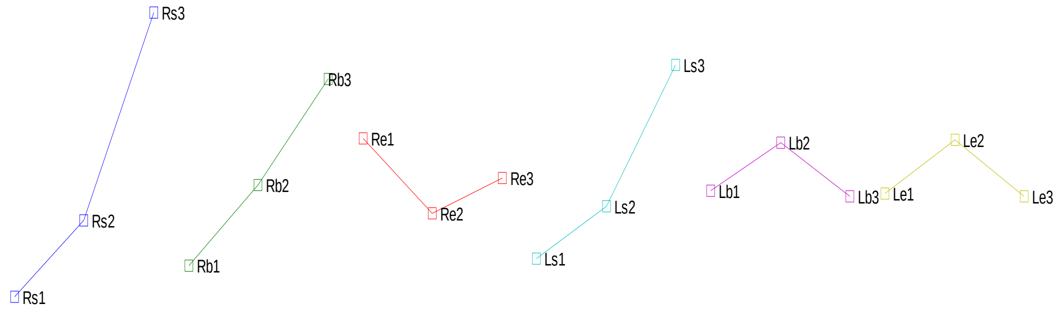
The values underlined in Table IX represent the highest values which were subsequently recalculated as the values of input parameters in Table II until the values for all six input parameters were maximized. As can be seen from Table IX, the variance ratio for parameter Re, Le of the RPM; Re, Lb and Le of the torque; Rb, Ls and Le of stator current are small. It means that all those parameters are identified as insignificant. High values for the calculated variance ratios means that they have significant effects on the outputs of the model. Therefore, the highest variance ratios are Rs and Lb of the rotational speed; Rs of the torque; Rs of the stator current, and are therefore the most influential parameters.

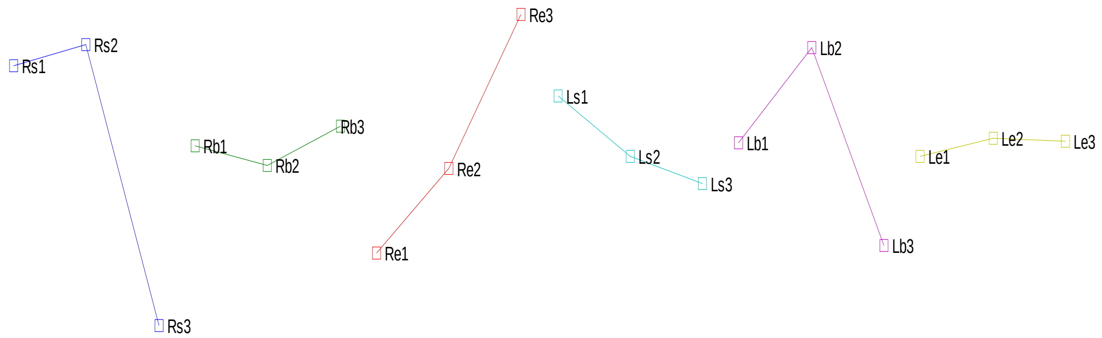
The graphical results using Taguchi method are shown in Fig.1.



a) S/N ratio of RPM



b) S/N ratio of torque



c) S/N ratioof stator current

Fig.1. Plots of evaluated S/N ratios

Here, the optimum conditions were: R_{s2} R_{b3} R_{e3} L_{s3} L_{b3} L_{e3} in the RPM.

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III. RESULTS AND DISCUSSIONS

The non-optimum input parameters are shown in Table X and the optimum input parameters are shown in Table XI

TABLE X
NON-OPTIMUM INPUT PARAMETERS AND OUTPUTS CORRESPONDING THE NON-OPTIMUM INPUT PARAMETERS

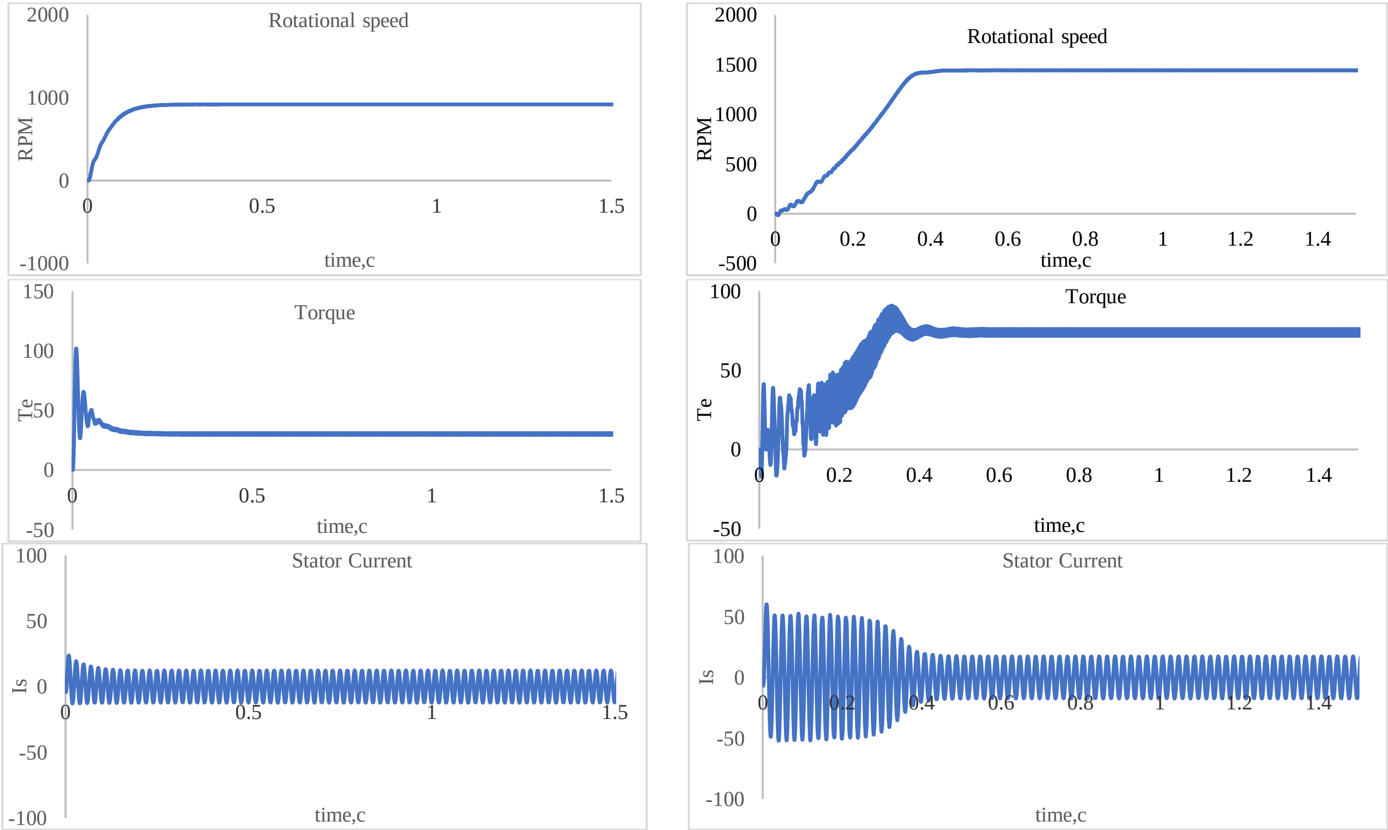
Input parameter	Notation	Optimum input values	Output parameters			Percentage to close to the target		
			RPM	Te	Is	RPM	Te	Is
						1450	73.69	20.8
Rotational speed (RPM)								
Resistance of stator	Rs	3.58	1449.76	74.62	20.18	99.98%	98.76%	97.03 %
Resistance of rotor bar	Rb	2.43E-05						
Resistance of rotor end-ring	Re	1.68E-06						
Inductance of stator	Ls	1.80E-02						
Inductance of rotor bar	Lb	1.93E-06						
Inductance of end ring	Le	1.14E-07						
Torque (te)								
Resistance of stator	Rs	4.37	1442.27	73.85	20.76	99.47%	99.79%	99.79 %
Resistance of rotor bar	Rb	3.64E-05						
Resistance of rotor end-ring	Re	1.66E-06						
Inductance of stator	Ls	1.78E-02						
Inductance of rotor bar	Lb	1.74E-06						
Inductance of end ring	Le	9.36E-08						
Stator Current (Is)								
Resistance of stator	Rs	3.98	1445.16	74.15	20.62	99.67%	99.39%	99.12 %
Resistance of rotor bar	Rb	3.31E-05						
Resistance of rotor end-ring	Re	1.37E-06						
Inductance of stator	Ls	1.98E-02						
Inductance of rotor bar	Lb	1.75E-06						
Inductance of end ring	Le	1.04E-07						

TABLE XI
OPTIMUM INPUT PARAMETERS AND OUTPUTS CORRESPONDING THE OPTIMUM INPUT PARAMETERS

Input parameter	Notation	Optimum input values	Output parameters			Percentage to close to the target		
			RPM	Te	Is	RPM	Te	Is
						1450	73.69	20.8
Resistance of stator	Rs	4.50	973.78	33.87	15.43	67.16%	45.96%	74.18 %
Resistance of rotor bar	Rb	3.31E-03						
Resistance of rotor end-ring	Re	1.00E-04						
Inductance of stator	Ls	1.98E-02						
Inductance of rotor bar	Lb	1.75E-06						
Inductance of end ring	Le	1.04E-07						

"Values at the optimum levels" means optimum inputs to make the minimum difference between outputs and targets. As shown in Table XI, each of the values at the optimum levels has produced different outputs. As can be seen in the torque and stator current columns in Table XI, stator current and torque are increasing, but rpm is decreasing compared to the value in the column for the optimum level of rotational speed. It means that the optimum inputs of rotational speed to make the minimum difference between output and targets of rotational speed could not make the minimum difference between output and targets of stator current and torque. From the results of this study, we have found that the Taguchi method is useful when optimizing single parameter performance characteristics. On the other hand, this method is too complicated a procedure to be used to determine input parameters for optimizing more than one output, simultaneously.

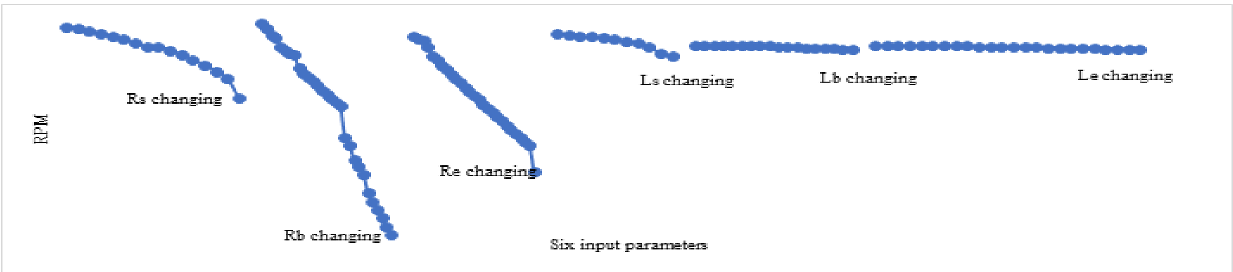
Outputs corresponding to the non-optimum and optimum input parameters for torque of the dynamic simulation are shown in Fig.2. For the stator current and rotational torque, the output of the dynamic simulation.



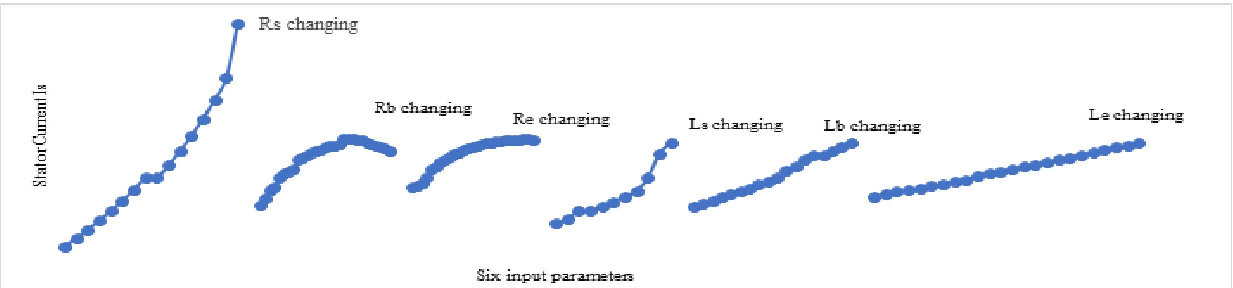
a) Non optimum input parameter b) optimum input parameter for Te

Fig.2. Outputs of the simulated motor

The relation between each of the six input parameters and three output parameters are studied based on the simulated motor (Fig.3). The effects on the three output parameters were obtained by changing the six parameters are changed one by one and keeping rest constant. Normalized values of the six inputs and three outputs are between 0 and 1.



a) Effects of each of the six input parameters on RPM



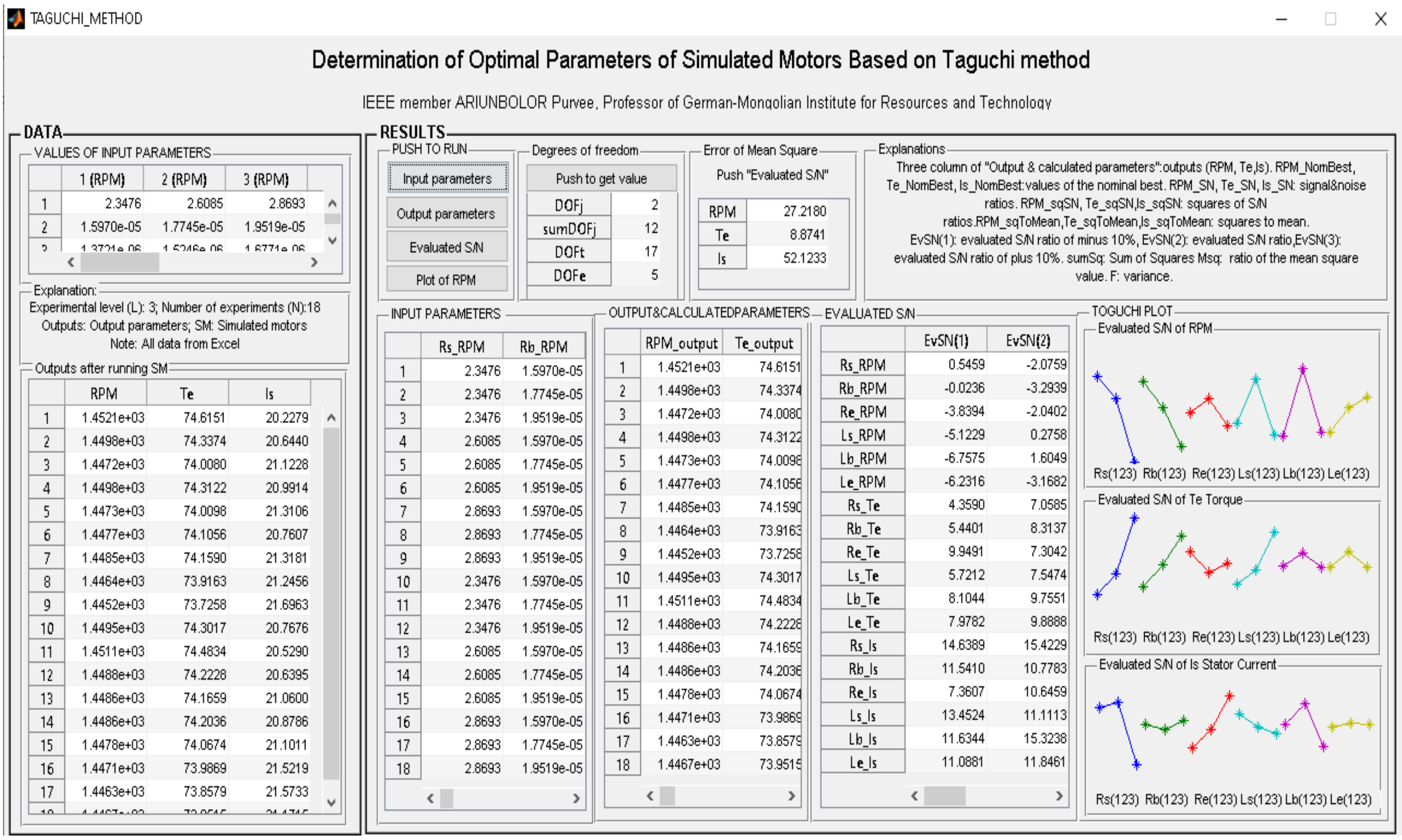
b) Effects of each of the six input parameters on stator current (Is)

Fig.3. Plots of the effects of each of the six input parameters

As shown in Figure 3 (a), all active resistances (Rs, Rb, Re) are the most important parameters influencing RPM. Do not greatly affect the RPM of the simulated motor. The higher the Rs resistance, the lower the RPM. Generally, it is concluded that RPM tends to increase as the values of all parameters (Rs, Rb, Re, Ls, Lb, Le) are decreased. Since the relation between RPM and Te torque are almost linear, the effects of the input parameters on the torque is not discussed here.

As shown in Figure 3 (b), expect for the stator current, all parameters, especially, stator resistance (Rs) and stator inductance are affected by stator current. The higher the Rs resistance, the higher the stator current. Actually, it is concluded that stator current tends to increase as the values of all parameters (Rs, Rb, Re, Ls, Lb, Le) are increased. Values higher than Rsa=6.992; Rb=3.64E-04; Re=2.19-05; Lls=2.77E-02; Llb=3.33E-06; and Lle=2.60E-07, shut down the simulated motors.

The software, using the Taguchi method to optimize the inputs for minimizing the difference between target and outputs, is shown in Fig.4 and the code for the MATLAB GUIDE (GUI) is shown [8]. This code includes all codes that are shown above; therefore, it easy to update and change to use other optimizations, using the Taguchi method.



IV. CONCLUSION

1) The determination of input parameters to the model, a simulated squirrel cage induction motor, which is as close to the nameplate data (rpm, stator current and torque) as possible, is based on the Taguchi method.
2) A new equation for calculating the evaluated S/N ratio is developed based on this research study.
3) The differences between output and nameplate data are reduced by using the calculation of the Taguchi method. Stator resistance was confirmed to be the most significant parameter.
4) After optimizing the inputs to get the outputs of the dynamic simulation, so as to achieve the targets (which are the nameplate parameters), we found that the technical configuration of the simulated motor achieved close approximation to the actual motor. Thus, in our next study, the motor we simulated using MATLAB will be used to create and understand behaviors of motor faults due to faulty bearings, rotor bars, eccentricity or stators, based on vibration and current spectrum analyses. Characteristic frequencies of faults (such as bearing, rotor, eccentricity) in the spectrum analyses can be calculated from the actual rpm of the motors. Therefore, studying the rpm is essential for any experiment to understand the defective frequencies.

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APPENDIX

PARAMETERS OF THE SIMULATED INDUCTION MACHINE

Name of parameter	Value	Unit	Name of parameter	Value	Unit
Data on the nameplate from the manufacturer			**Measured data from the laboratory:**		
Input voltages, V	415	V	Number of rotor bars	28	
Full load line current, A	20.8	A	Number of stator slots	36	
Rated power	11	kW	Number of stator coils/pole/phase	3	
Number of poles	4		Number of turns in the stator coils	20	
Speed, rpm	1450	RPM	Rotor stack length	0.15	m
Efficiency	0.89		Average radius	0.078	m
Power factor	0.83		Air gap average length	0.0006	m
Nominal torque	73.69	Nm	Stator resistance	3.2857	Ohm
Connection	delta		Stator leakage inductance	0.018	H
Calculated data			Rotor end ring resistance	1.39E-06	Ohm
Phase current in full load	11.96	A	Rotor end ring leakage inductance	9.36E-08	H
Synchronous speed	1500	rpm	Rotor bar resistance	3.71E-05	Ohm
Slip	0.033	%	Rotor bar leakage inductance	1.31E-06	H
Rotor angular velocity	151.8	rps	Stator layout: [1 10; 3 12; 20 11; 19 28; 21 30; 2 29; 13 22; 15 24; 32 23; 31 4; 33 6; 14 5; 7 16; 9 18; 26 17; 25 34; 27 36; 8 35]		
Rotor mechanical speed	24.17	Hz			
Rotor frequency	1.67	Hz			

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