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Dual stator winding variable speed asynchronous generator: optimal design and experiments

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Abstract. In the present paper is carried out a theoretical and experimental study of dual stator winding squirrel cage asynchronous generator (DSWA) behavior in the presence of saturation regime (non-sinusoidal) due to the variable speed operation. The main aims are the determination of the relations of calculating the equivalent parameters of the machine windings to optimal design using a Matlab code. Issue is limited to three phase range of double stator winding cage-induction generator of small sized powers, the most currently used in the small adjustable speed wind or hydro power plants. The tests were carried out using three-phase asynchronous generator having rated power of 6 [kVA].

1. Introduction

In the context of rapid technical progress, the electrical drives have to ensure an operation with high demands on change and adjustment of speed, starting, braking and reversing, respectively a movements correlation of working mechanisms of the same production unit. All these technical requirements have created prospects for the development of complex drive systems, using power electronic converters based on semiconductor components that provide automatic management of production processes, with a low energy, turning to computer and microprocessor [1], [2], [3].

Despite its simple and robust construction, the motion control for this type of generators should take into account the complexity of the dynamic model which is nonlinear and variable in time and that the physical parameters of the machine are not always known with great precision. Under these conditions the motion control means controlling the speed and/or the position, respectively torque control. As on obtain a faster torque response as the motion control is more efficient. Mainly there are two control strategies: scalar control and vector control [4], [5]. Usually, the electric machines are designed to be supplied in sinusoidal regime. If the generator is connected to the grid through a static frequency converter, because of the higher harmonics (non-sinusoidal regime), both its parameters and functional characteristics values will be more or less different from the case of sinusoidal power supply. The presence of these higher harmonics will have as result the appearance of a deforming and saturation regime in the machine, with adverse effects in general in its operation [4]. The appearance of the deforming regime in the machine is inevitable because any static frequency converter based on semiconductor technique produces voltages or currents, which contain, in addition to fundamental and harmonic, higher odd time harmonics.

The introduction of distributed generation through renewable sources of energy has opened a challenging area for power engineers. As these sources are intermittent in nature, variable speed electric generators are employed for harnessing electrical energy from these sources. However, power electronic control is required to connect these sources to the existing grid [6]. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counterparts, however, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads. The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems. Most turbine manufacturers have opted for reduction gears between the low speed turbine rotor and the high speed three-phase generators. Direct drive configuration, where a generator is coupled to the rotor of a wind turbine directly, offers high reliability, low maintenance, and possibly low cost for certain turbines [6], [7], [8], [9], [10], [11].

For small to medium power wind or hydro turbines, permanent magnet generators and squirrel cage induction generators are often used because of their reliability and cost advantages. Interconnection apparatuses are devices to achieve power control, soft start and interconnection functions. Very often, power electronic converters are used as such devices. Most modern turbine inverters are forced commutated PWM inverters to provide a fixed voltage and fixed frequency output with a high power quality. For certain high power wind or hydro turbines, effective power control can be achieved with double PWM (pulse width modulation) converters which provide a bidirectional power flow between the turbine generator and the utility grid [12], [13], [14], [5], [16], [17].

2. Optimal design

Many unknown parameters are involved in the design of the Dual Stator Winding Asynchronous Generator (DSWA). As a result, it is necessary to assign some description to these parameters. They will be further explored in the design equations. Table 1 gives a list of the parameters used in the design approach and their values.

Table 1. Preliminary Design Parameters.

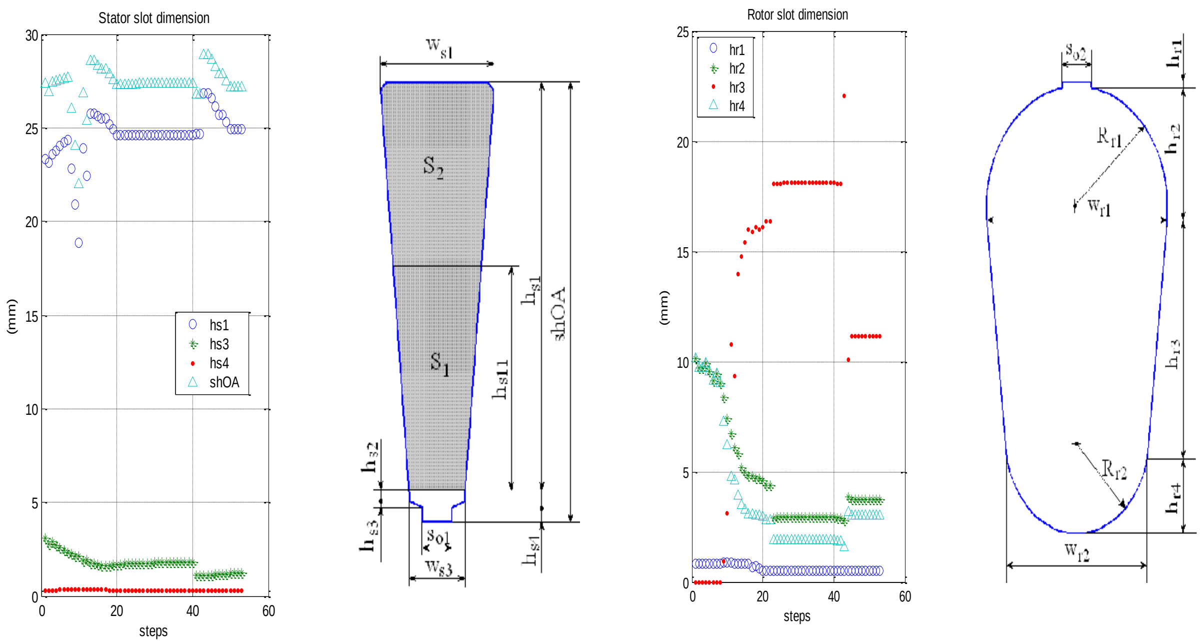
Symbol	Description	Value
p	number of poles	8
$\mathbf{D_{si}}$	inner stator diameter	180 mm
$\mathbf{D_{so}}$	outer stator diameter	267.8 mm
$\mathbf{N_{ss}}$	stator slots number	72
$\mathbf{N_{rs}}$	rotor slots number	58
$\mathbf{l_{i}}$	ideal core lenght	230 mm
$\mathbf{h_{ag}}$	air-gap height	0.35 mm
$\mathbf{k_{c}}$	Carter factor for air-gap	1.22
$\mathbf{h_{ss}}$	total height of stator slot	30.5 mm
μ_0	permeability of the air-gap	12.56 10^{-7} H/m
$\mathbf{h_{rs}}$	total height of rotor slot	31.5 mm
mwp	main winding position	up
layersm	number of layers of main winding	1
layerse	number of layers of excitation winding	2
ncme	number of elementary conductors on main winding	24
ncee	number of elementary conductors on excitation winding	24
$\mathbf{R_{m}}$	main winding phase resistance	2.4 Ω
$\mathbf{R_{e}}$	excitation winding phase resistance	3.78 Ω
$\mathbf{R_{r}}$	rotor phase resistance	2.36 Ω
$\mathbf{L_{\sigma m}}$	main winding leakage phase inductance	14.5 mH
$\mathbf{L_{\sigma e}}$	excitation winding leakage phase inductance	0.6 mH

Symbol	Description	Value
$\mathbf{L_{me}}$	mutual inductance between main and excitation winding	14 mH
$\mathbf{L_{\sigma r}}$	rotor winding leakage phase inductance	15.3mH
$\mathbf{S_{copper}}$	copper section	S_{1net} = 129 mm^2
	phase connection	Y
$\mathbf{I_s}$	stator current	I_1 = 10,38/6 A
$\mathbf{U_f}$	phase voltage	U_1 = 139/240 V
f	frequency	15 Hz
$\mathbf{P_n}$	rated power	6 kVA
n	speed	415 rpm
$\mathbf{U_{DC}}$	DC voltage	460 V
$\mathbf{k_e}$	main winding to excitation winding voltage ratio	24/31

The general optimization problem could be divided in three quasi-independent sub-problems: choosing the objective function, choosing the optimization variables and the machine model, and then solving the problem. The optimal design of the DSWA generator is subject to multi-objective criteria and constructive constrains such as: reducing the initial cost, reducing the generator size and weight, improving the efficiency, and limit the components temperature to a feasible level. The multi-objective criteria should be aggregated somehow in a single objective function if the design objective is to obtain a unique solution. This could be a total cost function including penalty for unmet constrains. The objective function, C_t becomes [19]:

$$C_t = C_i + C_E + C_a + C_p \ , \tag{1}$$

where C_i is the initial cost, C_E the cost of the lost energy, C_a additional cost to consider the impact of the machine size and finally C_p is the penalty cost. Sixteen optimization variables are used to control the machine main size dimensions as well the slots details. The probability to reach the global optimum using Hooke Jeeves (HJ) algorithm could be increased by starting the algorithm several times from different points of the optimization variable space [20]. A few sample results for the HJ optimization evolution to the best design are shown in figures 1, 2, 3 and 4.



a) **b)**

Figure 1. a) Optimal stator slot dimensions; b) optimal rotor slot dimensions.

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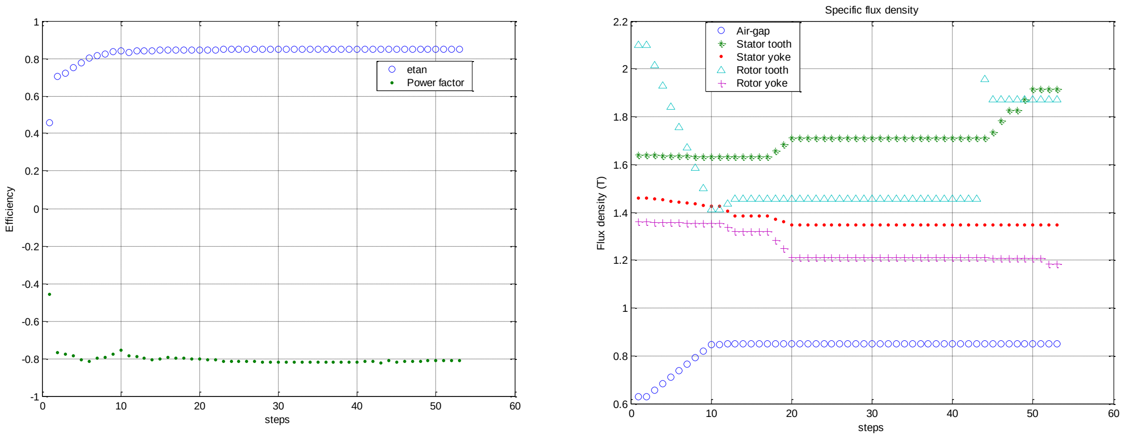
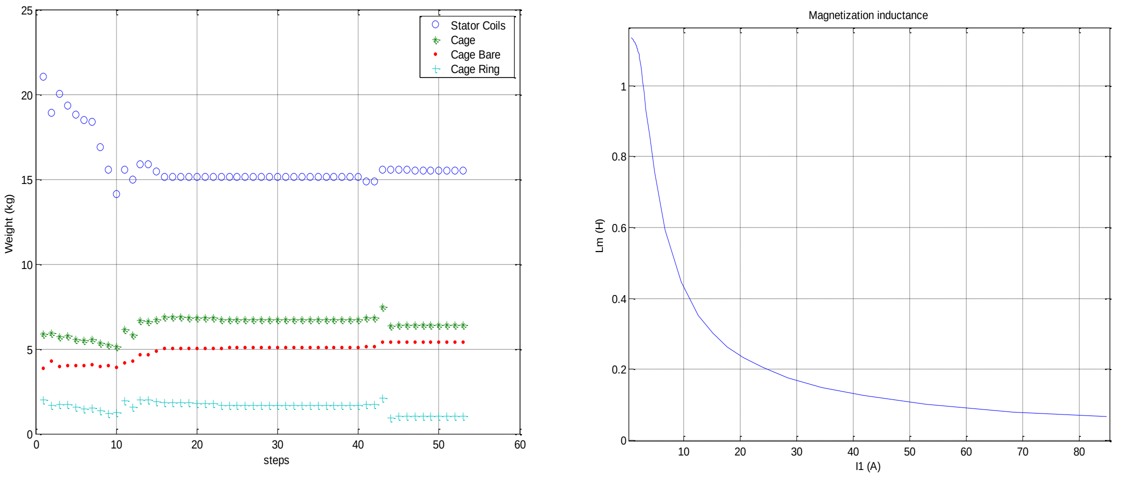


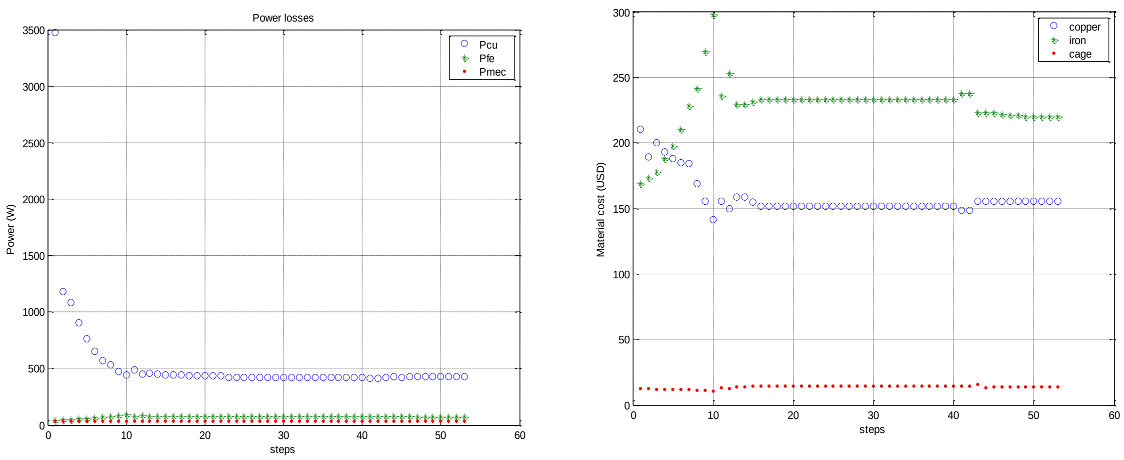
a) **b)**

Figure 2. a) Efficiency and power factor; b) specific flux density.



a) **b)**

Figure 3. a) Weight; b) magnetization inductance.



a) **b)**

Figure 4. a) power losses; b) material cost.

3. Experimental results

To prove the above design methods, a 6kVA 400V/415 rpm prototype of the DSWA generating system has been developed (Figure 5). The prime mover is simulated by a three-phase cage-type induction machine driven by an inverter of ABB ACS 800-11. The parameters of the prototype are given in Table 1. In experiments, the value of the auxiliary excitation capacitors is 35 μF, and the value of the filter inductances is 23 mH.

Figure 5. Generator DSWA coupled with prime mover induction motor under experimental tests.

Through the experimental tryouts it is desired, in a first step, the computation of the DSWA parameters and characteristics for the stationary regime and their comparison with the values obtained through optimal design and finite element analysis. In figure 6 the equivalent phase scheme of the machine is presented. Resistances R_m and R_e are measured in DC current and the inductances will be computed through no load (real and ideal) and short circuit methods.

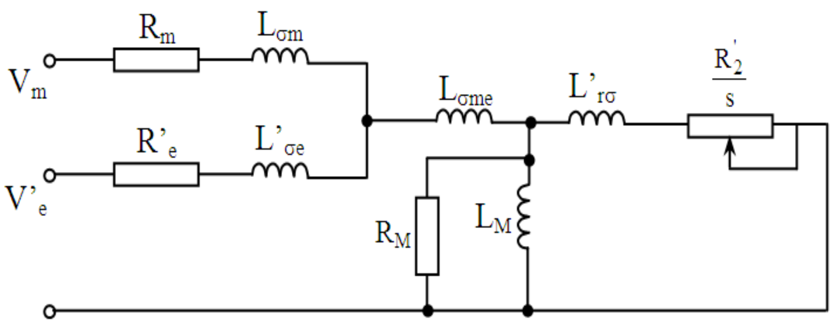


Figure 6. Equivalent phase scheme of the DSWA.

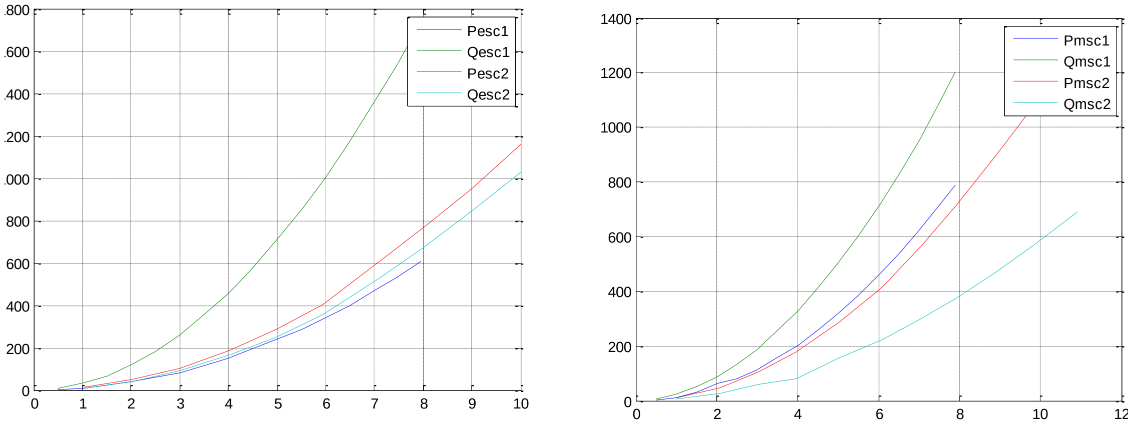
The results of the measurements are presented in tables 2 and 3. In Figures 7, 8, 9 and 10 are presented some experimental characteristics and parameters.

Table 2. Ideal no load probe with the main winding supplied from the AT and open circuit excitation.

Crt. no.	V_{Am} [V]	V_{Bm} [V]	V_{Cm} [V]	I_{Am} [A]	I_{Bm} [A]	I_{Cm} [A]	P [kW]	Q [kVar]	V_{Ae} [V]	V_{Be} [V]	V_{Ce} [V]	$I_{motor\ antrenare}$ [A]	n [rot/min]	Medie P [%]
1	271,53	270,08	269,56	2,29	2,29	2,36	0,21	1,85	256,9	258,0	256,6	11,6	750,1	0,52
2	253,74	253,13	251,78	2,12	2,12	2,18	0,21	1,62	240	240,7	239,8	11,65	750,2	1,045
3	231,05	228,92	229,96	1,92	1,91	1,94	0,12	1,32	218	219	218,5	11,6	749,9	1,405
4	213,68	212,41	212,06	1,74	1,74	1,77	0,06	1,12	202	203	202	11,65	749,9	1,585
5	190,81	190,52	190,12	1,55	1,56	1,57	0,03	0,89	181	182	180	11,65	750	1,865
6	173,32	172,22	172,45	1,40	1,41	1,43	0,02	0,73	164,5	165,6	164,5	11,6	749,8	1,48
7	156,58	154,61	155,02	1,28	1,26	1,25	0,03	0,59	147,3	149	148	11,55	749,5	1,57
8	138,21	136,14	136,31	1,11	1,11	1,09	0,03	0,45	129,5	131	130	11,65	749,6	1,32
9	115,76	113,68	114,14	0,93	0,92	0,89	0,04	0,31	108,5	109,8	108,5	11,6	749,8	1,375
10	95,20	93,18	93,59	0,78	0,78	0,74	0,01	0,22	89	90,4	89,3	11,65	749,6	1,385
11	74,59	73,15	73,78	0,63	0,59	0,59	0,01	0,13	69,8	70,8	70,2	11,6	749,5	1,355
12	57,79	56,52	57,21	0,49	0,46	0,46	0,01	0,08	54	55	54,5	11,6	749,8	1,37
13	43,58	42,49	43,18	0,38	0,35	0,35	0,01	0,05	40,5	41,4	41	11,6	749,8	1,225
14	29,38	28,75	29,21	0,28	0,25	0,26	0,00	0,02	27,3	27,8	27,6	11,6	749,7	1,32
15	15,18	14,55	15,01	0,16	0,14	0,14	0,00	0,01	13,8	14,4	14,1	11,6	749,6	1,285
16	6,23	5,95	6,52	0,08	0,06	0,06	0,00	0,00	5,7	5,9	6	11,65	749,6	1,285

Table 3. Short circuit probe for the main winding, which is supplied from the AT in two phases and open circuit excitation.

Crt. no.	V_{Am} [V]	V_{Bm} [V]	V_{Cm} [V]	I_{Am} [A]	I_{Bm} [A]	I_{Cm} [A]	P [W]	Q [Var]	V_{Ae} [V]	V_{Be} [V]	V_{Ce} [V]
1	7,7	0,1	7,7	0,52	0	0,52	4	8	4,18	8,08	4,13
2	13,4	0,2	13,5	1	0	0,98	12	24	7,28	13,92	7,25
3	19,7	0,2	19,8	1,52	0	1,52	30	52	10,57	20,16	10,55
4	25,6	0,2	25,8	2,04	0	2,02	65	90	13,65	26,05	13,66
5	31,0	0,3	31,2	2,5	0	2,5	80	134	16,41	31,42	16,47
6	36,4	0,3	36,7	3,	0	2,98	112	188	19,17	36,78	19,27
7	42,3	0,4	42,6	3,52	0	3,5	156	254	22,15	42,55	22,28
8	48,1	0,4	48,5	4,04	0	4,02	204	330	25,05	48,25	25,22
9	53,7	0,4	54,1	4,52	0	4,52	260	414	27,85	53,76	28,15
10	59	0,5	59,4	5	0	4,98	316	500	30,41	58,95	30,78
11	64,6	0,5	65,1	5,5	0	5,48	384	598	33,22	64,5	33,63
12	70,5	0,6	71	6,06	0	6,02	464	718	36,13	70,15	36,6
13	75,8	0,6	76,4	6,52	0	6,48	540	830	38,8	75,36	39,26
14	81,1	0,6	81,7	7,02	0	6,98	624	952	41,6	80,65	42,02
15	86,4	0,7	87,1	7,5	0	7,46	712	1084	44	85,8	44,7



a) **b)**

Figure 7. Short-circuit active and reactive power versus current: a) excitation winding; b) main winding.

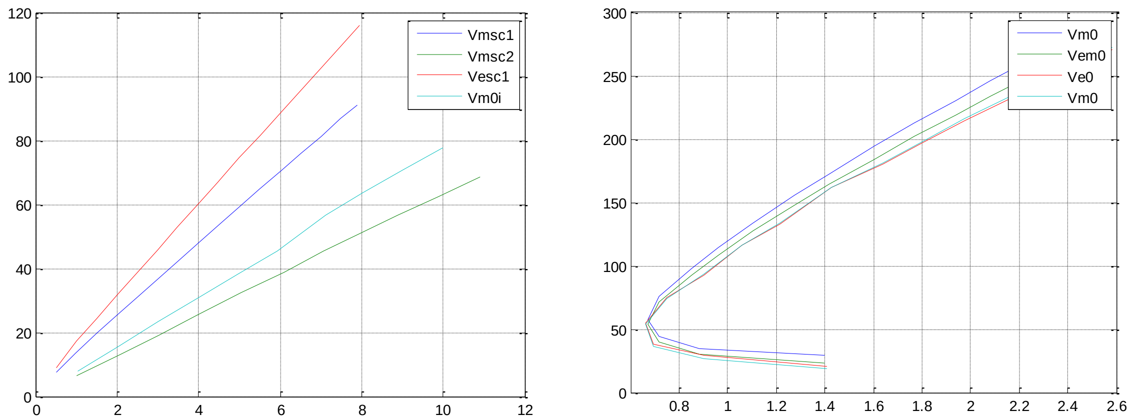


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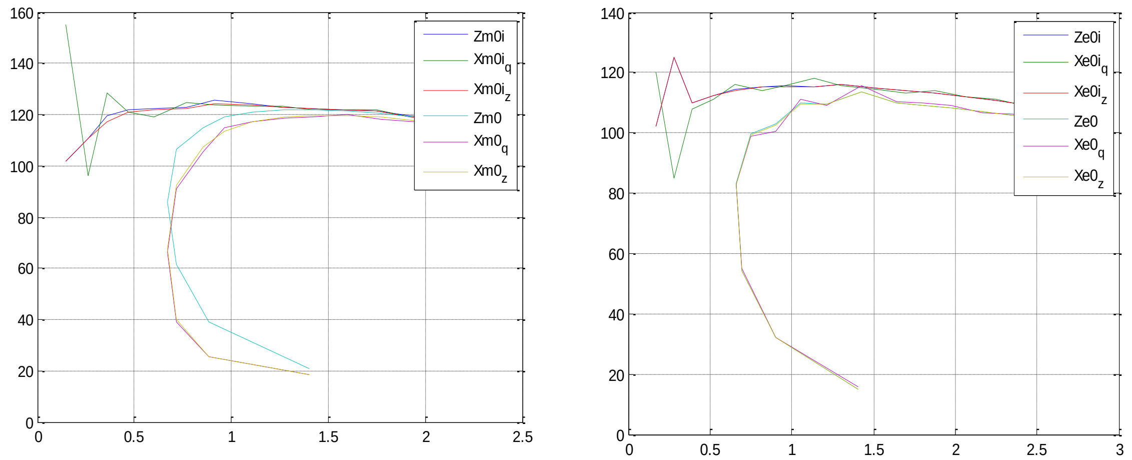
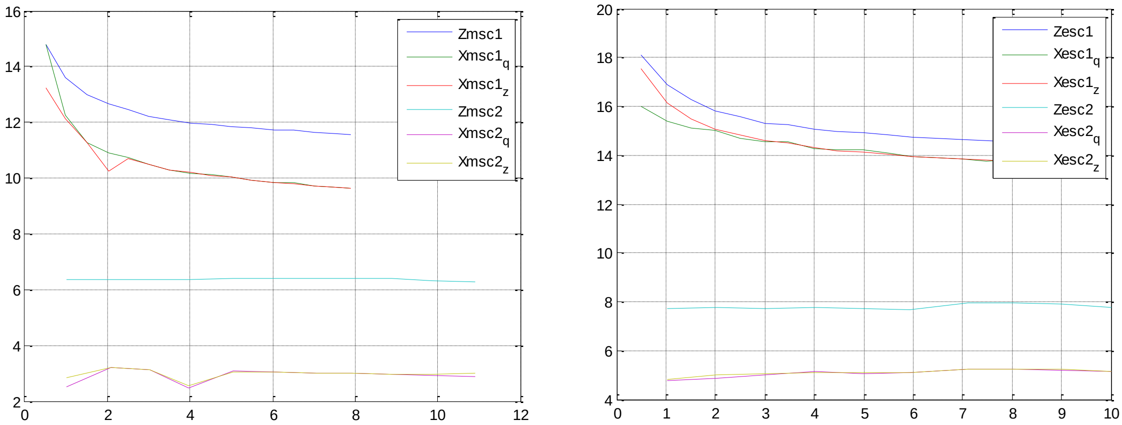
Figure 8. Voltages versus current: a) short-circuit; b) no load.



a) **b)**

Figure 9. Impedances and reactances versus current at no load: a) main winding; b) excitation winding.



a) **b)**

Figure 10. Impedances and reactances versus current at short-circuit: a) main winding; b) excitation winding.

4. Conclusions

In this paper was presented a new type of twin stator windings induction machine operating in generator mode. The main advantage of the DSWA is its improved capability to operate at variable low speed for wind or hydro power plants.

A mathematical perfectly saturated model should be implemented in flux rotating frame coordinate and then the transients and steady state magnetization inductance could be considered in the model.

The preliminary and optimal design had shown the parameters and performance complex dependence on the number of poles. However, the 16 poles generator is considered the optimum because it has the maximum efficiency, while the active material cost is also near its minimum and the power factor (which influences the power convertor cost) is not large.

In the experimental tests are prove quantitatively and qualitatively the good correlations with simulations, and the practicality of the proposed system for low power variable speed wind or hydro power plants applications.

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