A Brushless doubly fed induction machine with flat plane rotary transformers

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Abstract - This paper presents and analyses a 350kW brushless doubly fed three-phase induction machine with its wound rotor circuit connected to flat plane rotary transformers. It presents the advantages of substituting brushes and slip-rings by rotary transformers. In addition, it shows rotary transformer design and presents the doubly fed induction machine operation. The steady state model considers electrical circuit techniques to provide information about current, power factor and efficiency on load. Equivalent circuit parameters used on simulations were obtained through analytical calculation.

INDEX TERMS: ALTERNATING CURRENT MOTORS, BRUSHLESS MACHINES, CIRCUIT ANALYSIS, CIRCUIT SIMULATION, EQUIVALENT CIRCUITS, INDUCTION MOTORS, PROTOTYPE, ROTATING MACHINES, ROTARY TRANSFORMER;

NOMENCLATURE

Induction machine parameters:

V_{lm1} Stator winding line voltage (in volts).
V_{lm2} Rotor winding line voltage (in volts).
V_{m1} Stator winding single-phase voltage (in volts).
V_{m2} Rotor winding single-phase voltage (in volts).
I_{m1} Stator winding current (in amperes).
I_{mm} Magnetizing current (in amperes).
I'_{m2} Rotor winding current (in amperes).
P_{m1} Power absorbed/delivered to grid (in kilowatts).
$P_{air-gap}$ Power on the air-gap (in kilowatts).
P_{shaft} Mechanical power on shaft (in kilowatts).
f_{m1} Stator winding electric frequency (in hertz).
f_{m2} Rotor winding electric frequency (in hertz).
f_{mec} Mechanical frequency (in hertz).
f_{syn} Synchronous mechanical frequency (in hertz).
R_{m1} Stator winding resistance (in ohms).
X_{m1} Stator winding leakage reactance (in ohms).
R_{mfe1} Stator iron resistance (in ohms).
X_{mm} Magnetizing reactance (in ohms).
R'_{mfe2} Rotor iron resistance (in ohms).
R'_{m2} Rotor winding resistance (in ohms).
X'_{m2} Rotor winding leakage reactance (in ohms).
p_m Number of poles pairs.
s Slip of induction machine.

Rotary transformer parameters:

V_{t1} Stator winding single-phase voltage (in volts).
V_{t2} Rotor winding single-phase voltage (in volts).
I'_{t1} Stator winding current (in amperes).
I'_{tm} Magnetizing current (in amperes).
I'_{t2} Rotor winding current (in amperes).
S_t Apparent power of rotary transformer (in kilovoltamperes).
N_{t1} Number of turns at stator winding.
N_{t2} Number of turns at rotor winding.
a Transforming ratio.
R'_{t1} Stator winding resistance (in ohms).
X'_{t1} Stator winding leakage reactance (in ohms).
R'_{tfe1} Stator iron resistance (in ohms).
X'_{tm} Magnetizing reactance (in ohms).
R'_{tfe2} Rotor iron resistance (in ohms).
R'_{t2} Rotor winding resistance (in ohms).
X'_{t2} Rotor winding leakage reactance (in ohms).
R'_{ext} External resistance (in ohms).

1. INTRODUCTION

Three-phase induction machine is a popular motor for industrial application and a largely used generator in wind energy farms [1] - [3]. In this context doubly fed induction machines demands special attention regarding its features on torque and speed controllability [1] - [19]. Speed and torque can be controlled by rheostats or frequency converter via rotor winding. Connected to induction machine rotor circuit, the converter processes an amount of power proportional to rotor speed. This arrangement reduces converter power to a fraction of the total mechanical power, saving costs [1] - [7], [18]. figure 1 presents a doubly fed induction machine and its two terminal boxes.

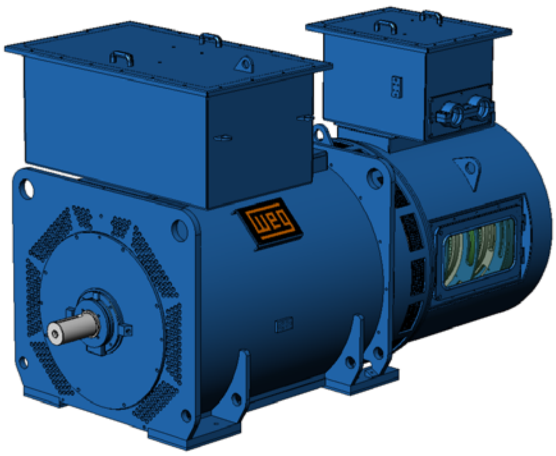

Figure 1 - Doubly fed three-phase induction machine

The benefits of doubly fed induction machines use are undeniable; nevertheless, to take advantages of them it is necessary to provide electrical connection between rotor winding and statics rheostat or frequency converter [1] - [19].
Nowadays, the most common way to access rotor winding is by brushes and slip-rings. However, the mechanical contact between moving slip-rings and static brushes wears these components and involves maintenance of them. Powder generated by brushes wearing can be also prejudicial for motor insulation. Additionally, any fault on electrical contact can generate sparks, limiting machine installation only to non-explosive environments [1] - [3].
Development of brushless technologies is very interesting for reducing maintenance costs and expanding the use of doubly fed machines to explosive atmospheres [1] - [14], [20].
Many studies consider the use of two induction machines connected in cascade for obtaining brushless devices. One possibility consists in mounting two individual machines (each one with its own rotor and stator) on the same shaft with electrical connection between their rotors windings [4]. Another one is represented by manufacturing a double winding stator and a special rotor cage able to join two different induction machines in one single frame [5] - [13].
The combination of two induction machines is effective at the view of eliminating brushes and slip-rings, but introduces superposition of two different torque behaviors. The result is a device with an anomalous torque vs. speed curve, in which synchronous speed is determined by the combination of each machine number of poles [4] - [6].
Only the combination of the induction machine with a device lacking in any torque would allow no changes on synchronous speed and on torque vs. speed curve shape [1].
Since the seventies, there is made several studies in order to substituting brushes and slip-rings by contactless energy transfer systems, as, for example, rotary transformers [20] - [28]. Initially, this device was developed concerning spacecrafts applications, where the lack of reliability and high rate of maintenance of brushes and slip-rings are totally undesirable [20].
In [22], Papastergiou and Macpherson propose rotary transformer as an alternative solution for contactless transfer of energy across the revolving frame of airborne electronic-scanning radar. In [30], Legranger et al. propose the replacement of gliding contacts of a wound rotor synchronous machine by an axial rotary transformer operating as contactless transmission power system.
Despite of some particularities, all of these usages for rotary transformer involve applications where the transformer is submitted to frequencies of hundreds of Hz [20] - [30].
In [1] - [3], nevertheless, Ruviaro et al. present the use of an axial three-phase rotary transformer electrically connected to an induction machine rotor circuit. Working with induction machine rotor frequency, the rotary transformer allows the access to rotor circuit without any mechanical contact. By using an appropriated drive, it is possible to control the induction machine to operate as a generator as well as a motor at almost any speed, except on synchronicity.
As well as conventional doubly fed induction machines, the solution presented in [1] - [3] is very convenient for systems that must generate constant frequency voltage by the use of variable speed devices, like wind turbines [1] - [19].
This paper shows main design aspects of a flat plane three-phase rotary transformer integrated to a doubly fed induction machine and its operation. Figure 1 and 2 present, respectively, the outside and inside part of a 350kW prototype design under construction at WEG Equipamentos Elétricos S.A.
All results presented on this paper are based equivalent circuit parameters analytical calculation of this prototype.

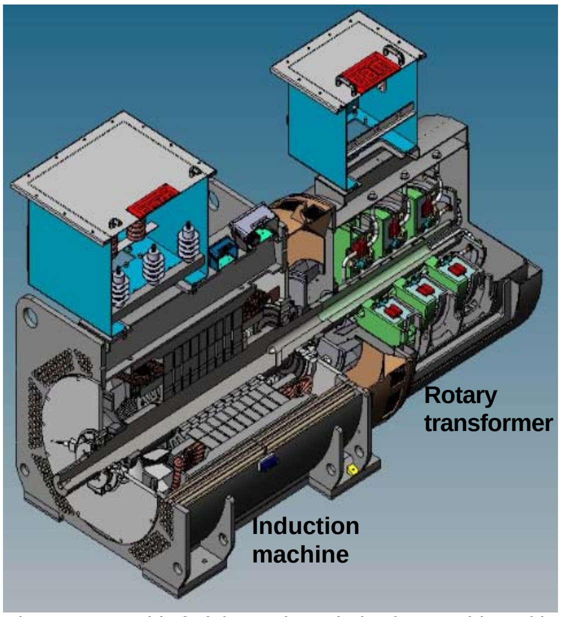

Figure 2 - Doubly fed three-phase induction machine with flat plane rotary transformer.

2. ROTARY TRANSFORMER DESIGN

Rotary transformer design [1] - [3], [20] - [28], different from conventional transformers, has the particularity of an air-gap to permit movement between primary (stator) and secondary (rotor) windings as can be observed in figure 3.

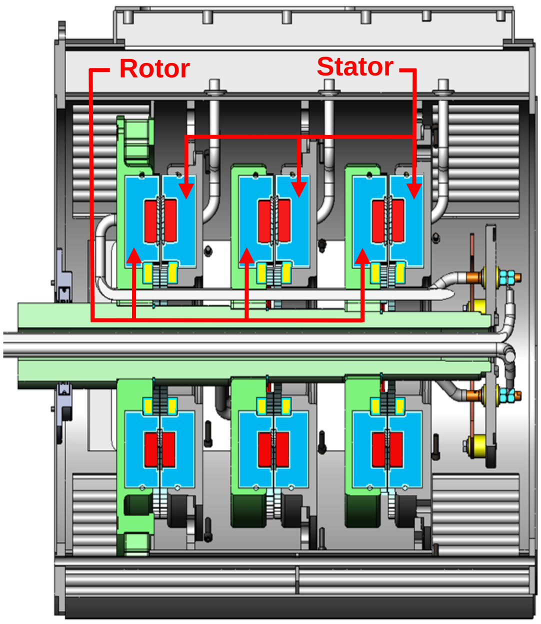

Figure 3 - Design of three-phase flat plane rotary transformer system.

The three transformers are shell-form with primary and secondary windings totally involved by the core. The option for 3 single-phase units design has the objective to reduce magnetizing flux unbalance on rotary transformer system. The presence of air-gap introduces reluctances that change the magnetic circuit in comparison to conventional transformers [1]. Like other devices for contactless energy transmission [5], rotary transformer has high leakage/ magnetizing reactance ratio.
Figure 4 and table 1 present main dimensions of each single-phase rotary transformer module.

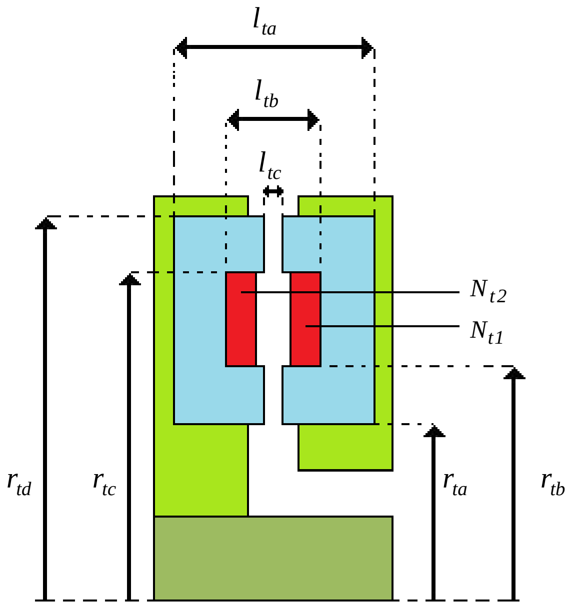

Figure 4 - Single-phase rotary transformer

Table 1 - Rotary transformer dimensions

r_{ta}	r_{tb}	r_{tc}	r_{td}	N_{t1}
137mm	184mm	255mm	302mm	20
l_{ta}	l_{tb}	l_{tc}	a	N_{t2}
145mm	64mm	3mm	1	20

In the developed prototype, rotary transformer core was made of laminated silicon steel. Lamination direction is longitudinal to the shaft. Figure 5 presents three-phase rotary transformer magnetizing flux behavior obtained via finite elements simulation.

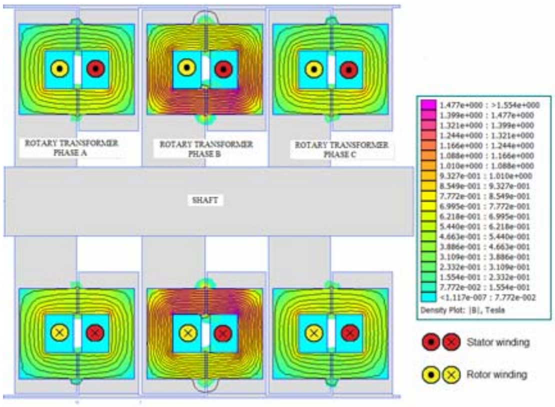

Figure 5 - Rotary transformer simulation by finite element method resources.

The permanent alignment of rotor and stator windings results in no slip between their magnetic fields. As consequence, flat plane rotary transformer produces no torque. Nevertheless, the magnetic attraction between transformer rotor and stator impacts in axial force on shaft. As consequence of this physic phenomenon, machine bearings must be designed to stand this effort.

3. DOUBLY FED INDUCTION MACHINE OPERATION

The doubly fed induction machine with rotary transformer is the set of a three-phase induction machine with 2pm poles stator winding directly connected to the electrical grid and a three-phase rotary transformer whose stator winding can be short-circuited or connected to rheostat banks or to electrical grid through a vector-controlled frequency converter [1] - [3].
Electrical connections for the use of converter are shown in figure 6. This configuration allows controlling torque, speed, power factor and current of induction machine by the converter connected to the stator winding of rotary transformer. The frequency converter controls the machine acting on amplitude, frequency and phase of voltage applied in stator winding of rotary transformer [1] - [6].

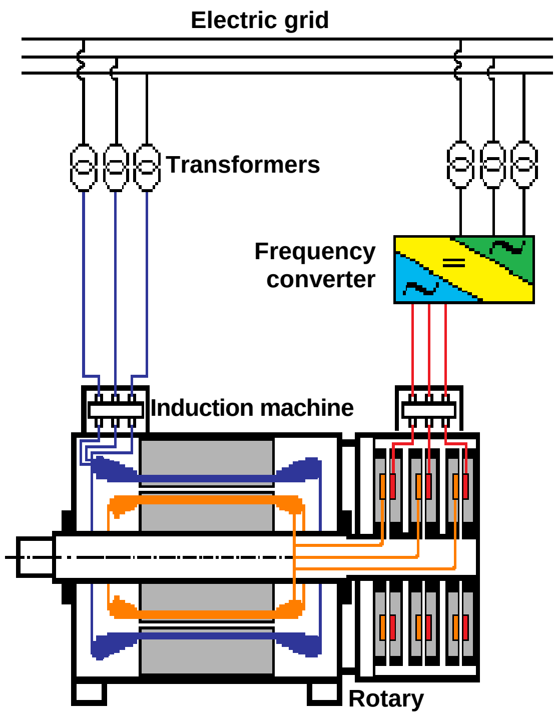

Figure 6 - Grid connection of the doubly fed three-phase induction machine with rotary transformer.

When the stator winding of rotary transformer is connected only to a resistive bank, it is possible to control torque, speed and current. However, power factor is not controllable [1] - [3].
In the built prototype, all electrical connections were in Y. Nevertheless, design for connection in D is perfectly possible.
The rotary transformer permits to adjust its stator voltage (Vt1) only changing the relation of turns (a) between the primary (Nt1) and secondary (Nt2) windings

$$V_{t1} = (N_{t1}/N_{t2}).V_{t2} = a.V_{t2} \qquad (1)$$

The only requirement is the same voltage for induction machine (Vm2) and rotary transformer rotor (Vt2) to avoid transformer core saturation

$$V_{m2} = V_{t2} \qquad (2)$$

The fundamental frequency of the air-gap induction wave generated by the induction machine stator winding induces a rotor winding current with electric frequency fm2 given by

$$f_{m2} = f_{m1} - p_m f_{mec} \qquad (3)$$

Rotor winding of the induction machine is electrically connected to rotor winding of the transformer; consequently their currents have the same electric frequency fm2.
Despite mechanical movement between rotor and stator transformer, there is no slip between their magnetic flux. Currents on rotor and stator windings are also in frequency fm2.
The synchronous mechanical frequency fsyn is

$$f_{syn} = f_{m1} / p_m \qquad (4)$$

The mechanical frequency of the shaft of the machine is

$$f_{mec} = (f_{m1} - f_{m2}) / p_m \qquad (5)$$

Equation (5) shows that it is possible to control the speed of induction machine by changing the frequency f_{m2} of the voltage on stator winding of rotary transformer [1] - [19].
When the converter is connected to stator winding of the transformer, as shown in figure 6, frequency, amplitude and phase of the voltage can be imposed on transformer stator, allowing in this way a complete control of the doubly fed induction machine. This control is not possible only at synchronous speed, when electric frequency on rotary transformer is null and it is impossible to transmit energy between its rotor and stator. This energy transference depends necessarily of alternating current presence.
Figure 7 shows the frequency on induction machine stator and induced frequencies on induction machine rotor and transformer windings. Induced electric frequencies are function of mechanical frequency or speed of machine shaft. The synchronous rotating frequency is represented by f_{syn}.

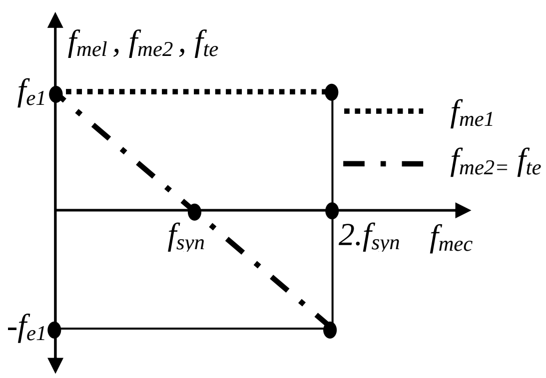

Figure 7 - Current frequency in induction machine and rotary transformer.

4. STEADY-STATE MODEL

The steady-state behavior is obtained through machine equivalent circuit [13]. Figure 8 presents the connection between windings of induction machine and the transformer.
From this model it is possible to analyze the machine operating at steady-state as motor and as generator.
All parameters are reflected to the stator of the induction machine.

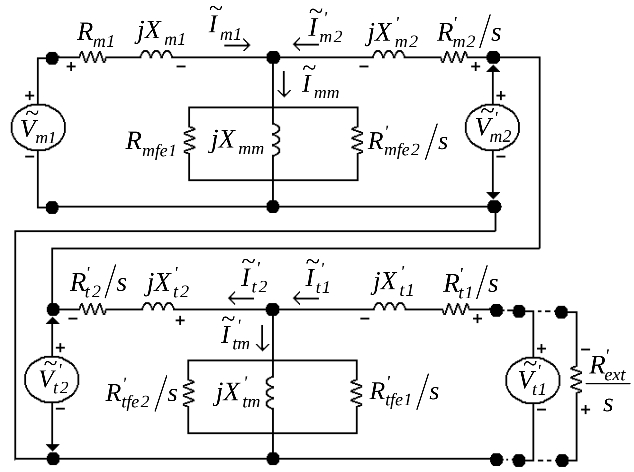

Figure 8 - Equivalent circuit of doubly fed induction machine with rotary transformer.

5. PROTOTYPE DATA

Nominal data of the 350kW brushless doubly fed three-phase induction machine prototype are shown in table 2.

Table 2 - Nominal data of the prototype

V_{lm1}	I_{m1}	f_{m1}	$2.p_m$	P_{shaft}	V_{lm2}	S_t
6600V	40A	60Hz	6	350kW	820V	350kVA

Table3 presents equivalent circuit parameters reflected to induction machine stator expressed in ohms.

Table 3 - Equivalent circuit parameters in ohms at 120ºC

R_{m1}	X_{m1}	R'_{m2}	X'_{m2}	R_{mfe1}	X_{mm}	R'_{mfe2}
1.170	6.660	1.496	8.240	8120	228.4	21000
R'_{t1}	X'_{t1}	R'_{t2}	X'_{t2}	R'_{tfe1}	X'_{tm}	R'_{tfe2}
0.593	3.202	0.593	3.202	15553	128.3	15553

6. STEADY-STATE MODEL RESULTS

By steady-state model and equivalent parameters circuit presented in table III, it is possible to obtain performance curves of the prototype.
Figure 9 displays power curves of the doubly fed three-phase induction machine with rotary transformer.

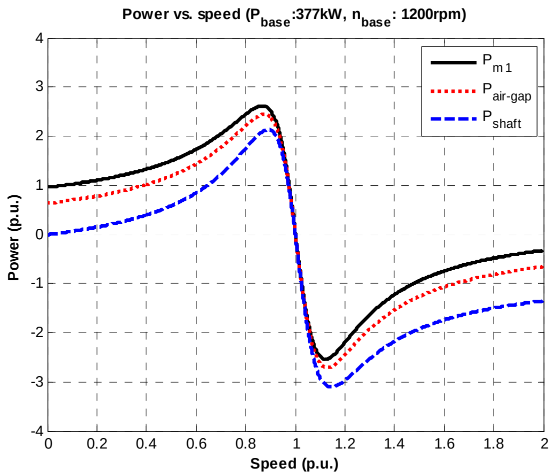

Figure 9 - Power for transformer stator winding short-circuited.

From 0 to 1 p.u. speed, the machine works as motor, transforming electrical power in mechanical power on shaft. From 1 to 2 p.u. speed, machine works as generator, converting mechanical power in electrical power injected on grid. Figure 10 shows the behavior of the diverse currents presented on the equivalent circuit from Figure 8.

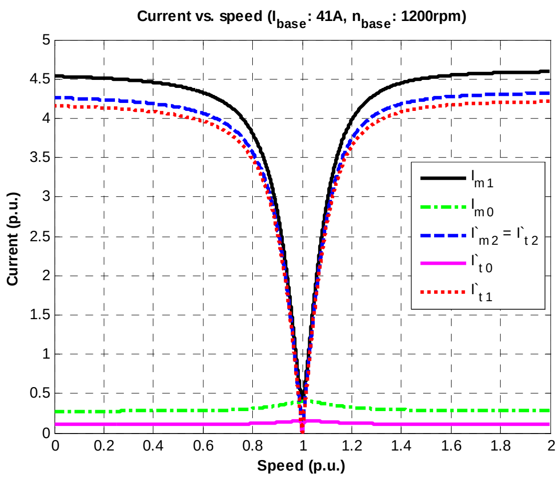

Figure 10 - Currents for short-circuited transformer stator winding.

Like a conventional induction machine, the minimum current is verified at synchronous speed, when no active power is delivered on shaft [1].
Figure 11 and 12 show that increasing external resistance to 2.R'm2, 5.R'm2 and 10.R'm2 (values referred to induction machine stator), it is possible to have higher starting torque and lower locked rotor current. The small decreasing on maximum torque value is consequence of transformer magnetizing reactance [1].

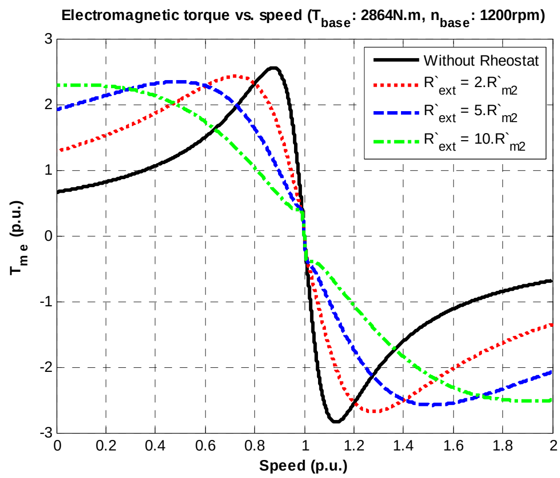

Figure 11 - Electromagnetic torques for transformer stator winding connected to external resistances.

The increasing of external resistance increases magnetic flux on rotary transformer, as can be observed at Figure 13.
Figure 14 shows electromagnetic torque behavior for external resistance values of $10.R'_{m2}$ (from 0 to 0.4 p.u. and 1.6 to 2.0 p.u.), $5.R'_{m2}$ (from 0.4 to 0.6 p.u. and 1.4 to 1.6 p.u.), $2.R'_{m2}$ (from 0.6 to 0.8 p.u. and 1.2 to 1.4 p.u.) and $0.R'_{m2}$ (from 0.8 to 1.2 p.u.). In figure 15 and 16 is possible to observe current and transformer magnetic flux behavior.

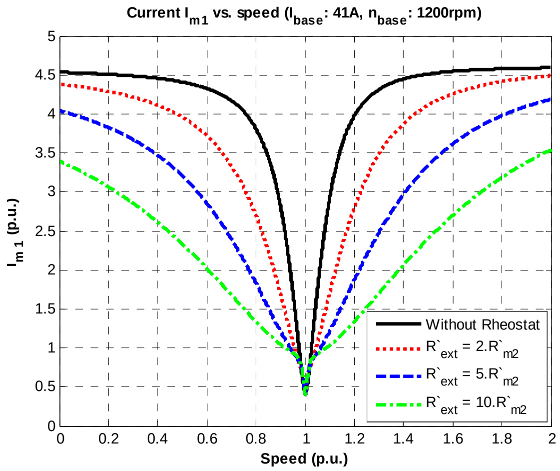

Figure 12 - Induction machine stator winding current for transformer stator winding connected to external resistances

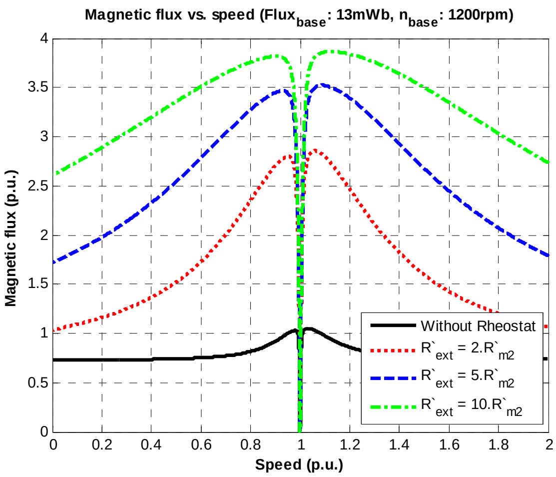

Figure 13 - Magnetic flux in rotary transformer for different external resistances connection

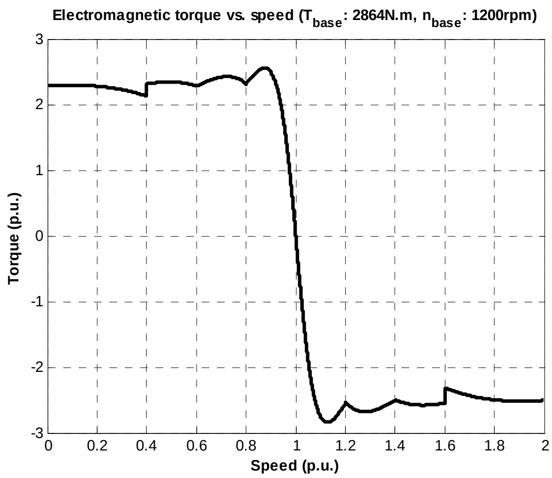

Figure 14 - Electromagnetic torque for transformer stator winding connected to variable external resistance.

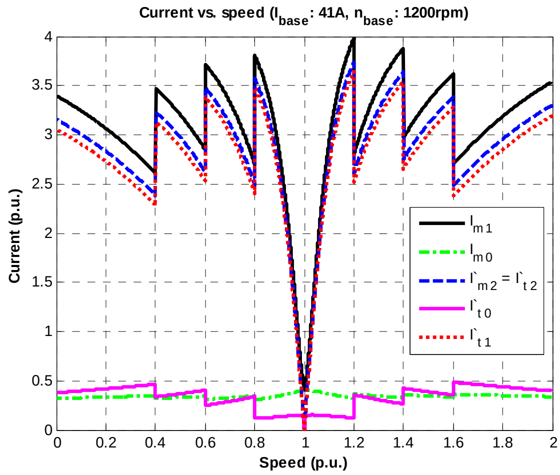

Figure 15 - Currents for transformer stator winding connected to variable external resistance

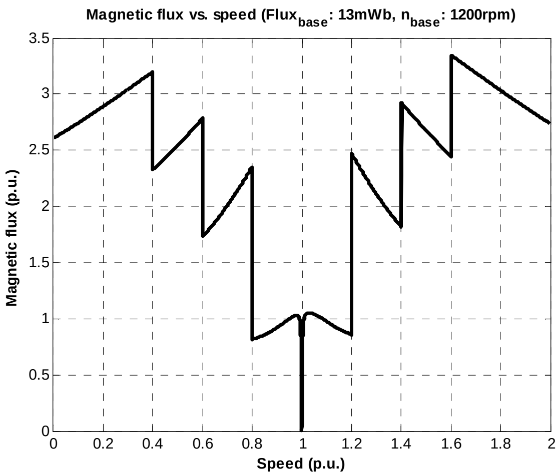

Figure 16 - Magnetic flux in rotary transformer for stator winding connected to variable external resistance.

In figure 16, it is possible to analyze rotary transformer magnetic flux behavior for external resistance changing. The connection of high external resistance impacts in high magnetic flux during machine starting. The consequence is axial attraction between rotor and stator. As the flat plane rotary transformer is mechanically connected to induction machine shaft, this axial force acts on its bearings. During design step, bearing specification must take account this phenomenon.

Tables IV and V present simulation results for 25% to 125% load for motor and generator regime. In both cases, rotary transformer stator winding is short-circuited.

Results for motor and generator regimes are close to each other. The main differences are related to speed, power absorbed or delivered to the grid and power factor.

Stray losses of 0.5% of power from grid and 5 kW of mechanical losses at 1200 rpm are considered in efficiency calculation.
Power factor verified for this prototype is smaller than standard values for conventional 6 poles induction machines. Obviously, this reduction on power factor is explained by the inductive nature of rotary transformer [1].

Table 4 - Induction machine with rotor connected to rotary transformer (motor operation)

Simulation results Motor Operation					
Load	**25%**	**50%**	**75%**	**100%**	**125%**
V_{lm1} (V)	6600	6600	6600	**6600**	6600
T_{shaft} (N.m)	716.7	1433.5	2144.7	**2864.3**	3572.9
P_{m1} (kW)	101.1	192.5	283.7	**376.6**	468.8
P_{shaft} (kW)	89.5	177.9	264.5	**350.8**	434.4
I_{m1} (A)	19.6	25.3	32.4	**40.5**	49.3
I_{t1} (A)	51.4	119.7	185.6	**253.1**	321.5
Efficiency (%)	88.6	92.5	93.3	**93.2**	92.7
Power factor	0.45	0.67	0.77	**0.81**	0.83
Speed (rpm)	1193	1185	1178	**1170**	1161

Table 5 - Induction machine with rotor connected to rotary transformer (generator operation)

Simulation results Generator Operation					
Load	**25%**	**50%**	**75%**	**100%**	**125%**
V_{lm1} (V)	6600	6600	6600	**6600**	6600
T_{shaft} (N.m)	715.9	1438.1	2148.2	**2865.8**	3576.2
P_{m1} (kW)	79.0	168.5	256.1	**344.0**	430.4
P_{shaft} (kW)	90.4	182.7	274.6	**368.6**	462.8
I_{m1} (A)	18.8	24.0	30.6	**38.2**	46.3
I_{t1} (A)	43.7	111.2	174.9	**238.9**	303.2
Efficiency (%)	87.4	92.2	93.3	**93.3**	93.0
Power factor	0.37	0.61	0.73	**0.79**	0.81
Speed (rpm)	1206	1213	1221	**1228**	1236

7. CONCLUSION

Substituting brushes and slip-rings is the greatest advantage of using rotary transformers in doubly fed induction machines. Avoiding mechanical contact between brushes and slip-rings, motors and generators maintenance can be drastically reduced. Additionally, with the studied device, the installation of wound rotor machines on explosive environments becomes possible. Moreover, this solution keeps all the benefits inherent to the use of induction machine rotor circuit for machine controlling.
Flat plane rotary transformer offers some advantages on prototype construction, but it represents axial force presence on induction machine bearings.
Steady stated model results give good expectations about the brushless doubly fed induction machine with flat plane rotary transformer under construction at WEG Equipamentos Elétricos S.A.

8. ACKNOWLEDGMENT

Authors wish to thank WEG Equipamentos Elétricos S.A. for the prototype building and the future use of its tests facilities.

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10. BIOGRAPHIES

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