STAND ALONE GENERATION SYSTEM USING SIX-PHASE INDUCTION MACHINE AND COMPONENT MINIMIZED CONVERTER

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***Abstract:* This work proposes a reduced switch count topology for energy generation system by using a six-phase induction machine and minimized voltage source converters to supply dc and ac isolated loads. The static topologies are composed by six-leg voltage source converter. The configurations were conceived to operate without the use of the load output inductor filter. The paper presents the control strategies for the system. The strategies are developed to be applied for isolated application where the prime mover power are not controlled, like the wind energy. Computer and experimental results demonstrate the feasibility of the systems proposed.**

***Keywords* – Generation system, six-phase induction machine, reduced switch count**

I. INTRODUCTION

The study of topologies with a reduced number of switches is an important topic in power electronics [1, 2, 5–7, 10, 13, 14]. The use of a six-phase induction motor to implement a high power drive system is an alternative to reduce the voltage and current ratings of the inverter power switches. This alternative also improves the reliability of the drive and makes possible to eliminate the common mode voltage [4,15]. However, those characteristics of the six-phase induction machine are little exploited for energy generator systems.

Single-phase to three-phase conversion topologies that do not use a boost inductor were proposed in [6] and studied in [1]. In a previous paper the authors have proposed ac/ac drives systems using four-phase and six-phase induction machine without use boost inductor [8]. In [12] it is proposed a generator system without load inductor filter but it can not optimize the power generated by prime mover or the voltage capacitor dc-bus.

This paper proposes a configuration for generation system by using a six-phase induction machine without using load inductor filter, addressed to three-phase generation system applications with machine control. The proposed six-phase induction generator topology is shown in Fig. 1. Besides saving the load inductor filter this configuration use less power devices than the standard three-phase inverter/six-phase rectifier (i.e., the eighteen-switch) ac/ac converter. Furthermore, the configuration uses the same number of switches as the three-phase ac/ac converters, i.e., the standard twelve-switch converter [11]

II. MACHINE DYNAMIC MODEL

The machine used in this work is a six-phase symmetrical machine (dual-machine) composed by two three-phase windings separated of $\pi/3$ rad away from each other. Adopting a fixed coordinate reference frame, the mathematical model that describes the dynamic behavior of the six-phase induction machine is given by

$$\begin{aligned}
\mathbf{v}_{sdq} &= r_s\mathbf{i}_{sdq} + \frac{d}{dt}\boldsymbol{\lambda}_{sdq} && (1)\\
\mathbf{v}_{rdq} &= r_r\mathbf{i}_{rdq} + \frac{d}{dt}\boldsymbol{\lambda}_{rdq} - j\omega_r\boldsymbol{\lambda}_{rdq} && (2)\\
\boldsymbol{\lambda}_{sdq} &= l_s\mathbf{i}_{sdq} + l_{sr}\mathbf{i}_{rdq} && (3)\\
\boldsymbol{\lambda}_{rdq} &= l_{sr}\mathbf{i}_{sdq} + l_r\mathbf{i}_{rdq} && (4)\\
\mathbf{v}_{sho} &= r_s\mathbf{i}_{sho} + l_{ls}\frac{d}{dt}\mathbf{i}_{sho} && (5)\\
\mathbf{v}_{rho} &= r_r\mathbf{i}_{rho} + l_{lr}\frac{d}{dt}\mathbf{i}_{rho} && (6)\\
\mathbf{v}_{sxy} &= r_s\mathbf{i}_{sxy} + l_{ls}\frac{d}{dt}\mathbf{i}_{sxy} && (7)\\
\mathbf{v}_{rxy} &= r_r\mathbf{i}_{rxy} + l_{lr}\frac{d}{dt}\mathbf{i}_{rxy} && (8)\\
T_e &= Pl_{sr}(i_{sq}i_{rd} - i_{sd}i_{rq}) && (9)\\
P\left(T_e - T_m\right) &= J\frac{d\omega_r}{dt} + F\omega_r. && (10)
\end{aligned}$$

where $\mathbf{v}_{sdq} = v_{sd} + jv_{sq}$, $\mathbf{i}_{sdq} = i_{sd} + ji_{sq}$, and $\boldsymbol{\lambda}_{sdq} = \lambda_{sd} + j\lambda_{sq}$ are the voltage, current and flux dq vectors of the stator, respectively; $\mathbf{v}_{sxy} = v_{sx} + jv_{sy}$, $\mathbf{i}_{sxy} = i_{sx} + ji_{sy}$, and $\boldsymbol{\lambda}_{sxy} = \lambda_{sx} + j\lambda_{sy}$ are the voltage, current and flux xy no-torque vectors of the stator, respectively; $\mathbf{v}_{sho} = v_{sh} + jv_{so}$, $\mathbf{i}_{sho} = i_{sh} + ji_{so}$, and $\boldsymbol{\lambda}_{sho} = \lambda_{sh} + j\lambda_{so}$ are the voltage, current and flux ho homopolar no-torque vectors of the stator, respectively (the equivalent rotor variables are obtained by replacing the subscript s by r); T_e is the electromagnetic torque; T_m is the prime mover torque; ω_r is the angular frequency of the rotor; r_s and r_r are the stator and rotor resistances; l_s, l_{ls}, l_r and l_{lr} are the self and leakage inductance of the stator and rotor, respectively; l_{sr} is the mutual inductance; P, J and F are the machine pole pairs, the moment of inertia and viscous friction coefficient, respectively.

The $dqxyoh$ stator variables of the previous model can be determined from the 123456 variables by using the transforming equation given by

$$\mathbf{w}_{s123456} = \mathbf{A}_s\mathbf{w}_{sdqxyoh} \qquad (11)$$

where $\mathbf{w}_{s123456} = [w_{s1} \;\; w_{s2} \;\; w_{s3} \;\; w_{s4} \;\; w_{s5} \;\; w_{s6}]^T$,

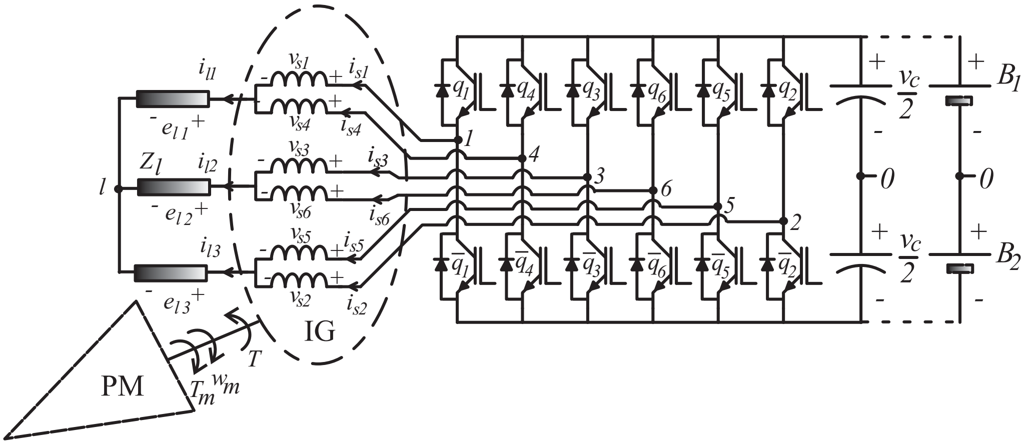


Figura 1 Six-phase induction generator system.

$\mathbf{w}_{sdqxyoh} = [w_{sd}\ w_{sq}\ w_{sx}\ w_{sy}\ w_{so}\ w_{sh}]^T$ and

$$\mathbf{A}_s = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & 1 & 0 & \frac{1}{2}\sqrt{2} & \frac{1}{2}\sqrt{2} \\ \frac{1}{2} & \frac{1}{2}\sqrt{3} & -\frac{1}{2} & \frac{1}{2}\sqrt{3} & \frac{1}{2}\sqrt{2} & -\frac{1}{2}\sqrt{2} \\ -\frac{1}{2} & \frac{1}{2}\sqrt{3} & -\frac{1}{2} & -\frac{1}{2}\sqrt{3} & \frac{1}{2}\sqrt{2} & \frac{1}{2}\sqrt{2} \\ -1 & 0 & 1 & 0 & \frac{1}{2}\sqrt{2} & -\frac{1}{2}\sqrt{2} \\ -\frac{1}{2} & -\frac{1}{2}\sqrt{3} & -\frac{1}{2} & \frac{1}{2}\sqrt{3} & \frac{1}{2}\sqrt{2} & \frac{1}{2}\sqrt{2} \\ \frac{1}{2} & -\frac{1}{2}\sqrt{3} & -\frac{1}{2} & -\frac{1}{2}\sqrt{3} & \frac{1}{2}\sqrt{2} & -\frac{1}{2}\sqrt{2} \end{bmatrix}$$

Vectors $\mathbf{w}_{s123456}$ and $\mathbf{w}_{sdqxyoh}$ can be voltage or current or flux vectors.

III. SYSTEM MODEL

The first configuration proposed in this paper is shown in Fig. 1(a). It uses six legs (twelve switches) and a capacitor bank at the *dc*-bus. The converter is composed by switches q_1, $\overline{q}_1$, q_2, $\overline{q}_2$, q_3, $\overline{q}_3$, q_4, $\overline{q}_4$, q_5, $\overline{q}_5$, q_6 and $\overline{q}_6$. The conduction state of the switches is represented by an homonymous binary variables q_j or $\overline{q}_j$ ($j = 1$ to 6): $q_j = 1$ or $\overline{q}_j = 1$ indicate closed switches, while $q_j = 0$ or $\overline{q}_j = 0$ indicate open switches. Pairs $q_1\overline{q}_1$, $q_2\overline{q}_2$, $q_3\overline{q}_3$, $q_4\overline{q}_4$, $q_5\overline{q}_5$ and $q_6\overline{q}_6$ are complementary.

The converter pole voltages are given by

$$v_{j0} = v_{sj} + e_{l1} + v_{l0} = (2q_j - 1)\frac{v_c}{2};\ j = 1 \text{ and } 4 \quad (12)$$
$$v_{j0} = v_{sj} + e_{l2} + v_{l0} = (2q_j - 1)\frac{v_c}{2};\ j = 3 \text{ and } 6 \quad (13)$$
$$v_{j0} = v_{sj} + e_{l3} + v_{l0} = (2q_j - 1)\frac{v_c}{2};\ j = 2 \text{ and } 5. \quad (14)$$

where v_c is the *dc*-bus voltage, v_{sj} ($j = 1$ to 6) are the machine phase voltages, e_{li} ($i = 1$ to 3) are the load voltages and v_{l0} is the neutral load voltage referred to the *dc*-bus mid-point $'0'$.

The phase voltage can be obtained from (12)-(14) as follows

$$v_{sj} = v_{j0} - e_{l1} - v_{l0};\quad j = 1 \text{ and } 4 \quad (15)$$
$$v_{sj} = v_{j0} - e_{l2} - v_{l0};\quad j = 3 \text{ and } 6 \quad (16)$$
$$v_{sj} = v_{j0} - e_{l3} - v_{l0};\quad j = 2 \text{ and } 5. \quad (17)$$

From (15)-(17) and (11) the *dqxyh* voltages can be given by

$$v_{sd} = \frac{1}{\sqrt{3}}(v_{10} + \frac{v_{20}}{2} - \frac{v_{30}}{2} - v_{40} - \frac{v_{50}}{2} + \frac{v_{60}}{2}) \quad (18)$$
$$v_{sq} = \frac{1}{2}(v_{20} + v_{30} - v_{50} - v_{60}) \quad (19)$$
$$v_{sx} = \frac{1}{\sqrt{3}}(v_{10} - \frac{v_{20}}{2} - \frac{v_{30}}{2} + v_{40} - \frac{v_{50}}{2} - \frac{v_{60}}{2}) - \sqrt{3}e_{l1} \quad (20)$$
$$v_{sy} = \frac{1}{2}(\frac{v_{20}}{2} - \frac{v_{30}}{2} + \frac{v_{50}}{2} - \frac{v_{60}}{2}) + e_{l2} - e_{l3} \quad (21)$$
$$v_{sh} = \frac{1}{\sqrt{6}}(v_{10} - v_{20} + v_{30} - v_{40} + v_{50} - v_{60}). \quad (22)$$

Only variables xy depend on e_{l1}, e_{l2} and e_{l3}. To make explicit that the xy voltages depend on the load voltage, new variables $x'y'$ were introduced, such that $v'_{sx} = v_{sx} + \sqrt{3}e_{l1}$ and $v'_{sy} = v_{sy} - e_{l2} + e_{l3} = v_{sy} - 2e_{l2} - e_{l1}$. In this case, the terms depending on the load voltages are incorporated in the stator xy model (7), which becomes

$$\mathbf{v}'_{sxy} = r_s\mathbf{i}_{sxy} + l_{ls}\frac{d}{dt}\mathbf{i}_{sxy} + \mathbf{e}_{lxy} \quad (23)$$

where

$$\mathbf{e}_{lxy} = e_{lx} + je_{ly} = \sqrt{3}e_{l1} - j(2e_{l2} + e_{l1}). \quad (24)$$

Assuming that i_{sj} ($j = 1$ to 6) are the machine phase currents, i_{sdqj} ($j = 1$ to 6) and i_{sxyj} ($j = 1$ to 6) are the part of the machine phase currents only associated to dq and xy currents, respectively, the following relations can be defined

$$i_{sj} = i_{sdqj} + i_{sxyj};\quad j = 1 \text{ to } 6. \quad (25)$$

where

$$i^*_{sdq1} = -i^*_{sdq4} = i^*_{sd}/\sqrt{3}$$
$$i^*_{sdq3} = -i^*_{sdq6} = (\sqrt{3}i^*_{sq} - i^*_{sd})/(2\sqrt{3})$$
$$i^*_{sdq5} = -i^*_{sdq2} = -(i^*_{sd} + \sqrt{3}i^*_{sq})/(2\sqrt{3})$$

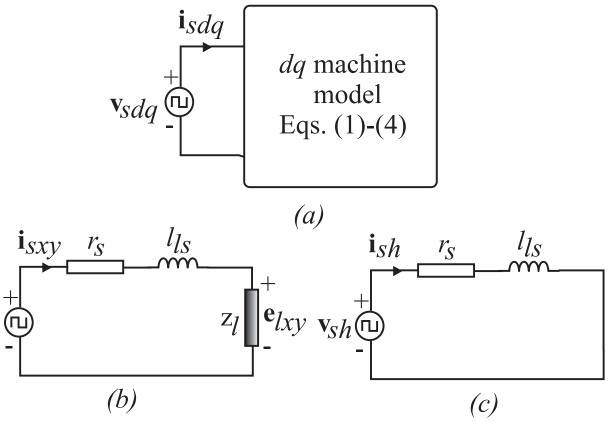


Figura 2 Diagram models for the dq, xy and h variables.

obtained from (11) with $i_{sx} = i_{sy} = i_{so} = i_{sh} = 0$, and

$$\begin{aligned} i_{sxy1} &= i_{sxy4} = i_{sx}/\sqrt{3} \\ i_{sxy3} &= i_{sxy6} = -(i_{sx} + \sqrt{3}i_{sy})/(2\sqrt{3}) \\ i_{sxy5} &= i_{sxy2} = (-i_{sx} + \sqrt{3}i_{sy})/(2\sqrt{3}) \end{aligned}$$

obtained from (11) with $i_{sd} = i_{sq} = i_{so} = i_{sh} = 0$.

Since $i_{s1} + i_{s4} = -i_{l1}$, and $i_{s3} + i_{s6} = -i_{l2}$, it follows that

$$i_{l1} = -2i_{sx}/\sqrt{3}; \quad i_{l2} = (i_{sx}/\sqrt{3} + i_{sy}). \tag{26}$$

or

$$i_{sx} = -\frac{\sqrt{3}}{2}i_{l1}; \quad i_{sy} = i_{l2} + \frac{1}{2}i_{l1}. \tag{27}$$

Considering (23), (24) and the machine model (1)-(8), the model diagram for the dq, xy and h variables can be defined as depicted in Fig. 2. Note that these three models are decoupled and only the xy model is coupled with the load voltages. Furthermore, the h variables must be controlled to be zero.

IV. PWM CONTROL

Generically, if the desired machine phase voltages are specified by v_{si}^*, ($i = 1$ to 6), given the load voltages e_{l1}, e_{l2} and e_{l3}, then from (12)-(14) the reference mid-point voltages can be expressed as

$$\begin{aligned} v_{j0}^* &= v_{sj}^* + e_{l1} + v_{l0}^*; \quad j = 1 \text{ and } 4 && (28) \\ v_{j0}^* &= v_{sj}^* + e_{l2} + v_{l0}^*; \quad j = 3 \text{ and } 6 && (29) \\ v_{j0}^* &= v_{sj}^* + e_{l3} + v_{l0}^*; \quad j = 2 \text{ and } 5. && (30) \end{aligned}$$

Note that these equations cannot be solved unless v_{l0}^* is specified. In the configuration I, the voltage v_{l0}^* can be calculated as a function of the apportioning factor μ as considered for the three-phase converter [9], [3]. It can be shown that v_{l0}^* is given by

$$v_{l0}^* = E(\frac{1}{2} - \mu) - (1 - \mu)v_{sM}^* - \mu v_{sm}^*. \tag{31}$$

where $v_{sM}^* = max\{\mathbf{V}\}$ and $v_{sm}^* = min\{\mathbf{V}\}$ with $\mathbf{V} = \{v_{s1}^* + e_{l1}, v_{s2}^* + e_{l3}, v_{s3}^* + e_{l2}, v_{s4}^* + e_{l1}, v_{s5}^* + e_{l3}, v_{s6}^* + e_{l2}\}$.

Since $v_{sM}^* - v_{sm}^* \leq E$, the dc-bus voltage necessary must satisfy restrictions given by

$$E \geq 2V_{dq}/\sqrt{3} \ \text{ if } \ V_{dq} \geq \frac{3E_l + \sqrt{3}V_{xy}}{2 - \sqrt{3}} \tag{32}$$

$$E \geq (V_{dq} + \sqrt{3}E_l + V_{xy}) \ \text{ if } \ V_{dq} < \frac{3E_l + \sqrt{3}V_{xy}}{2 - \sqrt{3}} \tag{33}$$

where V_{dq} and E_l are the dq and load amplitude voltages, respectively, and V_{xy} is the amplitude of the reduced voltage associated to the drop voltage due to the load current across the xy impedance.

The pulsewidths are determined from v_{10}^* to v_{60}^*, as given in (28)-(30) and (31)

$$\tau_j = (\frac{1}{2} + \frac{v_{j0}^*}{E})T; \qquad j = 1 \text{ to } 6 \tag{34}$$

V. CONTROL STRATEGY

The overall control of the system is based on two mode of operation.

Mode I: the power generated by the prime mover is maximized and the surplus of power do not absorbed by the load is saved in a dc-bus battery or dissipated in the dc bus resistor. In this mode when a wind power turbine is used, an optimum utilization of power, is possible controlling the machine speed via $\omega_m^* = \lambda_o V/R$, where ω_r^* is the machine reference speed, V is the wind speed, R is the rotor radius of the turbine, and λ_o is the optimal speed coefficient. An alternative to achieve this optimum use of power is to impose the electromagnetic torque of the machine as proportional to the square of its speed, that is $T_e^* = K\omega_r^2$.

Mode II: the power generated by the prime mover is indirectly regulated by the voltage capacitor dc-bus whose output is the machine torque. In this mode only the power required by the load and the system losses is received from the prime move.

In both modes the load voltage control is achieved by using the xy voltages. Also, the machine torque control, which includes the flux control, is accomplished by controlling the dq currents (as in field oriented control) or the dq voltage (as in volts/hertz control).

Since the dq and xy models and the dq and xy reference variables are independent, the dq currents can be independently controlled by the dq voltages and load voltages can be controlled by the xy voltages.

Fig. 3 shows the control block diagram for the $dq - xy - h$ based control technique for the modes I or II (selected at the torque control input). The torque control defines the reference I currents i_{sq}^* (for example, if the field oriented control is used: the machine torque and rotor flux controllers define the rotor field-oriented dq currents). The load voltages are regulated by using the controller R_{vxy}. The capacitor voltage v_c (dc-bus voltage) is adjusted to a reference value by using the controller R_{vc}, when mode II is used.

In Fig. 3 blocks R_{ixy}, R_{idq} and R_{ih} implement the xy, dq and h voltage and currents control, respectively.

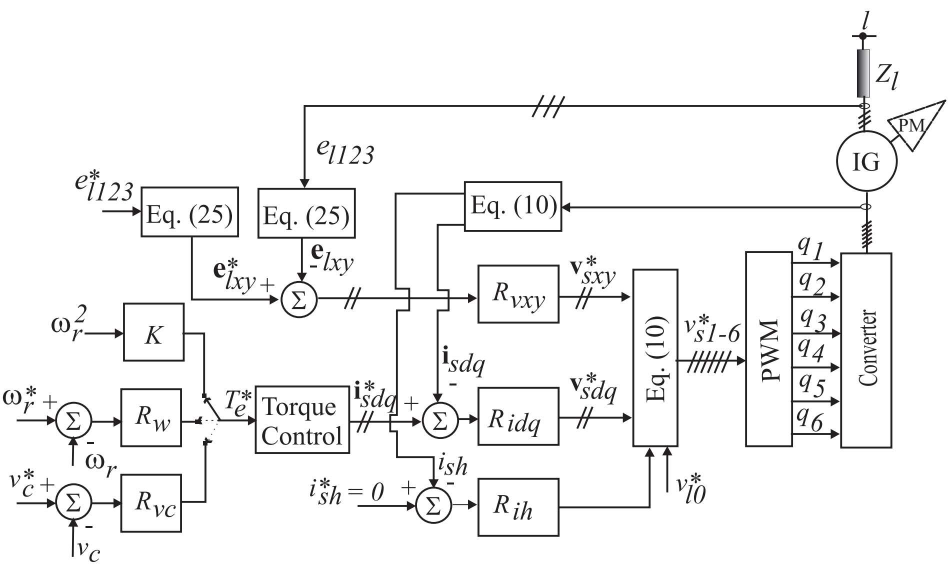


Figura 3 Block diagram of control.

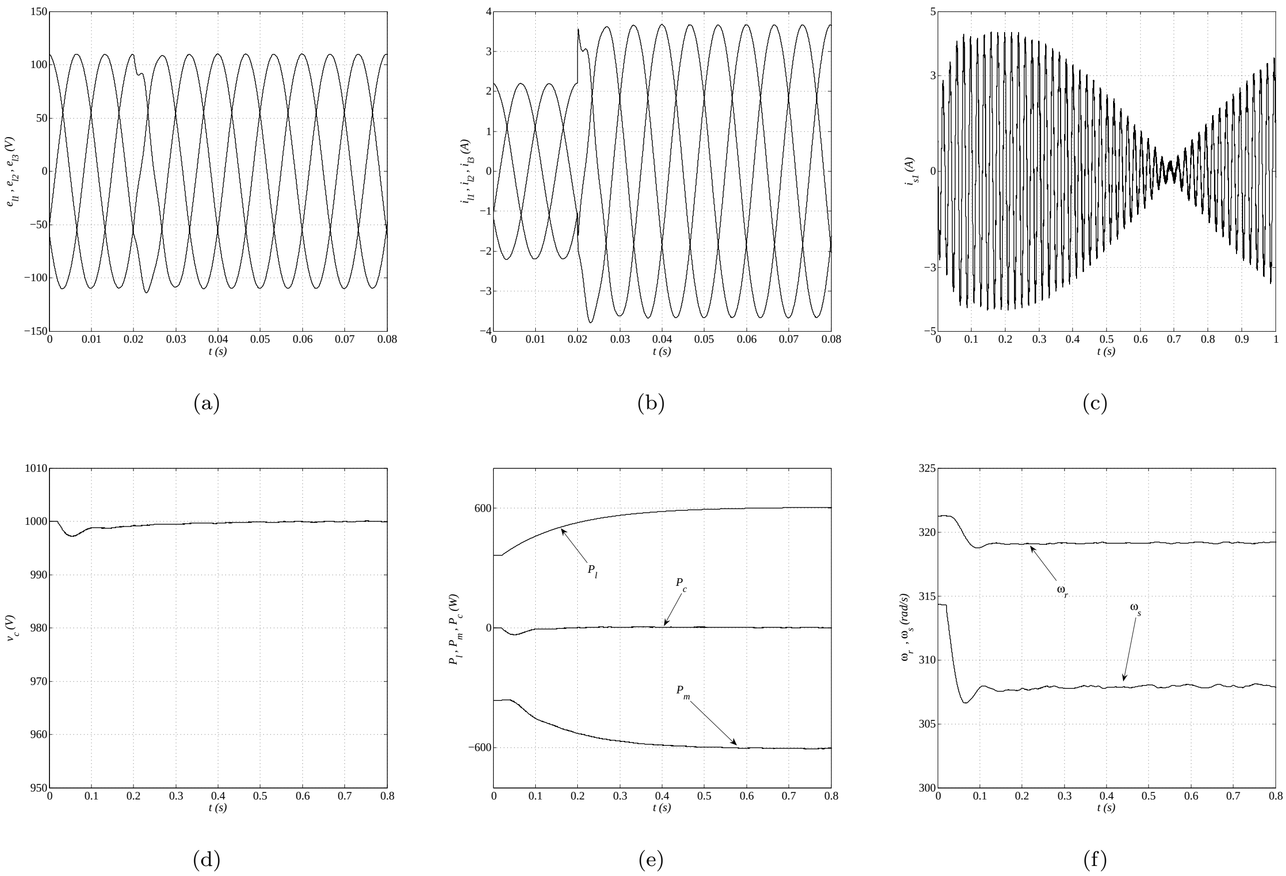
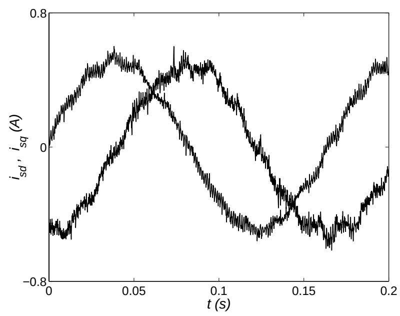


Figura 4 Simulation result: a) load voltages, (b) load currents, (c) machine current for phase 1 (d) capacitor voltage, (e) capacitor, load and prime mover powers and (f) speed and frequency of the machine.

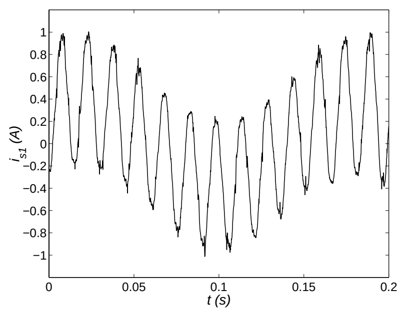
VI. SIMULATION RESULTS

The system presented in Fig. 1 have been studied by simulation supplying a RL load. In the tests the switching frequency was $10kHz$ and $C = 1000\mu F$. The load frequency was set to $f_l = 50\ Hz$. The system operates in Mode II. The load voltage was controlled and the volts-hertz strategy was used to control the machine torque.

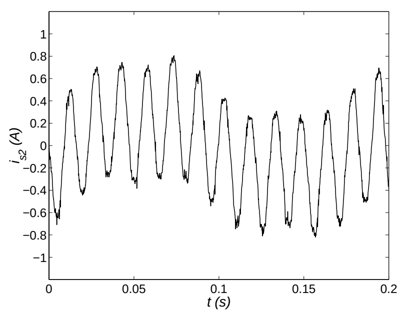
The simulation results were obtained to study a load transient. In the test the load resistance is reduced of



(a)



(b)



(c)

Figura 5 Experimental results for Configuration I: (a) i_{sd} and i_{sq}, (b) i_{s1}, (c) i_{s2}.

60% at $t = 0.02s$. Simulations results are shown in Fig. 4. The six parts of this figure are: (a) load voltages, (b) load currents, (c) machine current for phase 1 (d) capacitor voltage, (e) capacitor, load and prime mover powers and (f) speed and frequency of the machine. The overall behavior of the system is adequate. Particularly, it can be noted that the load voltage regulation is effective.

VII. EXPERIMENTAL RESULTS

The topology presented in Fig. 1 operating has been tested. In the tests the switching frequency was $10kHz$ and $C = 1000\mu F$. The set-up used in the experimental tests is based on a microcomputer (PC-Pentium) equipped with appropriate plug-in boards and sensors.

A preliminary experimental result, with the machine operating as motor, is shown in Fig. 5. This figure presents the dq machine currents (Fig. 5(a)), the machine currents for phase 1 (Fig. 5(b)) and phase 2 (Fig. 5(c)). The load and machine currents are controlled at $60Hz$ and $6Hz$, respectively. It can be noted that the overall control is adequate.

VIII. CONCLUSIONS

This paper has presented a generation system topology using a six-phase induction generator and component minimized converter without load inductor filter.

The operation principles of these topologies have been discussed. The results shown that the overall performance are adequate and the feasibility of the proposed configuration.

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