Working zones of an AC Autonomous Switched Reluctance Generator

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Abstract. In this paper it is described the behaviour in steady-state of a Switched Reluctance (SR) machine working in generating mode. Contrary to a standard SR motor working in generating mode to brake the machine in this work it is considered an AC autonomous self-excited generator where the phase inductance resonates with a capacitance yielding to almost sinusoidal currents and voltages. Along an oscillating cycle the machine experiments several kinds of energy transformation among electric, magnetic and mechanic. The paper describes step by step all these possible working zones that the machine experiments within a cycle. For this purpose, the flux linked by a phase as a function of phase current is studied. The linear case is first simulated and the nonlinear case later. To compare the results the peak of phase linked flux is maintained constant. In both cases the output voltage quality is considered through the Total Harmonic Distortion (THD). Additionally, the delivered power is considered under nonlinear conditions.

Key words

AC Switched Reluctance Generator, Self-excited Generator, Autonomous Generator.

1. Introduction

Switched Reluctance Motor (SRM) is well known due to its robustness, easy assembly, good performance and low manufacture costs [1]. Recently it has been reported its use as Alternative Current (AC) self-excited generator [2]. Consequently, its favourable properties can be advantageously used for generating in harsh environments. In this work the different situations that the machine experiments within an AC period are described. For this purpose, the flux linked by a phase as a function of phase current is studied. The phase inductance together with an external capacitor and the load modelled by a resistor forms a RLC circuit that is self-excited and exhibits parametric oscillator behaviour [3] where the pumping action is on its variable reluctance [4]. Synchronous reluctance self-excited generator has been studied analyzing the capacitance requirement [5]. The steady-state behaviour of an autonomous synchronous reluctance generator has been analysed in [6]. Although many aspects of variable reluctance generator have been studied, no much information is available for switched reluctance machines where there is double saliency in rotor and stator. The presence of capacitor means extracting electrical energy from the machine arriving from the stored magnetic energy or from the prime mover. In this sense, from the load point of view, in an AC SR generator, the generation mode is obtained using both the negative and positive slopes of the phase inductance profile. Strictly speaking the generation mode is only when the energy arrives from the prime mover. This only happens when the inductance profile is negative. The scheme for AC generation allows using the magnetic circuit in two quadrants and position sensors are not necessary. Completing this work we show that both sides of the inductance profile can be used to generate power. Besides, the AC voltage can have acceptable distortion for stepping up the output voltage by using a transformer or can be used in applications as in rectifiers where a small distortion is acceptable. The results at this time are only supported by simulations. For this purpose, a simulator has been implemented using Matlab/Simulink blocks where a hypothetical inductance profile has been used as an input to process the equations describing the circuit. In a real situation the inductance profile to be used should be obtained by FE simulation. In what follows it is first shown the circuit elements and their equations, then the steady-state behaviour is described, and the linked flux versus current enclosed area is analysed. The characteristic states and functioning modes are illustrated with an example and, finally, same

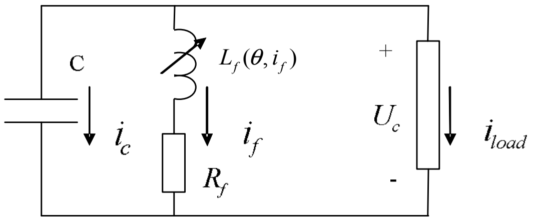

Fig 1. Single phase model

discussion on the obtained AC voltage quality and the average power drawn by the load is shown.

2. Circuit model of a single phase generator

Fig. 1 depicts the circuit elements of a single phase generator. Fig. 2 is the elemental generator having a single phase. For the sake of simplicity it is assumed a non saturation situation and negligible small series resistance R_f. Later, we will consider the effect of nonlinear magnetic characteristic in the simulated results. The basic circuit equations are

$$
\begin{aligned}
&U_c - R_f \cdot i_f = \frac{d\Phi(\theta, i_f)}{dt} \\
&\Phi(\theta, i_f) = L_f(\theta, i_f) \cdot i_f \\
&C\frac{dU_c}{dt} = -\left(i_f + i_{load}\right)
\end{aligned}
\tag{1}
$$

Where $\Phi(\theta, i_f)$ is the phase linked flux. Inductance is a nonlinear function of relative rotor-stator pole position and its phase current. Phase current can saturate the poles, especially when they overlap.

3. Trajectories and energy transformation.

The working zones that the machine experiments within a cycle are derived form the trajectories followed on the

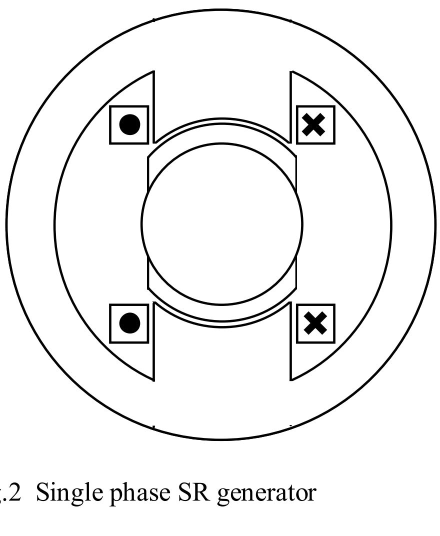

Fig.2 Single phase SR generator

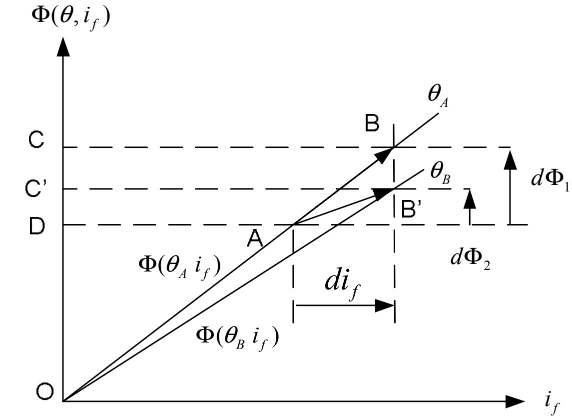

Fig. 3. Trajectory A-B' implies that $L_f(\theta_A, i_{fA}) \cdot di_f - d\Phi_2 > 0$. Area OAB' is the mechanical energy supplied to the machine. Area DAB'C' is electrical energy supplied to the machine. Both are stored in the machine as magnetic energy. Trajectory AB implies that $L_f(\theta_A, i_{fA}) \cdot di_f - d\Phi_2 = 0$. It only stores electrical energy supplied to the machine as magnetic energy (area DABC).

diagram of the flux linked by a phase as a function of phase current. The linear case is first simulated and the nonlinear case later. To compare the results the peak of phase linked flux is maintained constant.
By using (1), the machine supplies electrical energy if,

$$d\Phi(\omega t, i_f) \cdot i_f < 0 \tag{2}$$

As the phase stores magnetic energy, strictly speaking (2) does not mean that the machine is in generating mode. It could even happen that stored magnetic energy is both used to return mechanical energy to the prime mover and to supply energy to the capacitor and the load. As already stated, the generation mode only holds when the energy arrives from the prime mover.

A. Linear case

In the linear case the different operating modes can be obtained by checking the energy balance along the trajectory between two near points A-B as in Fig. 3.
If the rotor is on the same position θ_A then the condition $L_f(\theta_A, i_{fA}) \cdot di_f - d\Phi_1 = 0$ is met.
This trajectory only stores electrical energy supplied to the machine as magnetic energy (area DABC). The trajectory AB' implies a rotor displacement from θ_A to θ_B and $L_f(\theta_A, i_{fA}) \cdot di_f - d\Phi_2 > 0$. Area OAB' is the mechanical energy supplied to the machine. Area DAB'C' is electrical energy supplied to the machine. Both are stored in the machine as magnetic energy. In general, the condition that indicates that the machine gets energy from the prime mover is

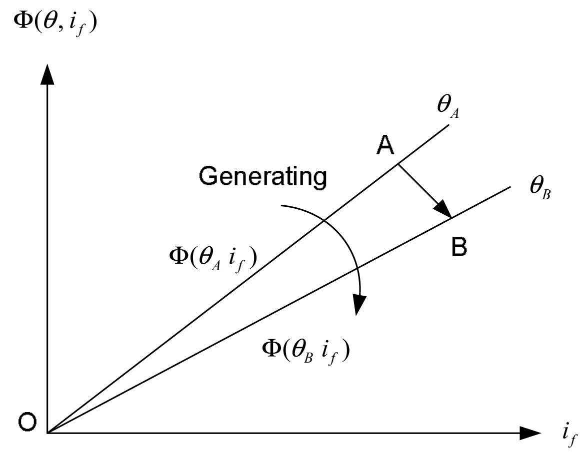

Fig.4. Clockwise scanned area OAB showing the mechanical energy transformed into magnetic and/or electrical energy.

$$L_f(\theta_A, i_{fA}) \cdot di_f - d\Phi_A > 0 \tag{3}$$

Generation mode can be interpreted graphically as shown in Fig. 4. The machine is generating when the magnetic curve $\Phi(\theta_A, i_{fA})$ containing the starting point A is over the characteristic $\Phi(\theta_B, i_{fB})$ containing the end point B. Along the followed trajectory A-B the area scanned and enclosed between both curves represents the mechanical energy transformed into electrical energy. Generation implies that the area is scanned clockwise. If point B returns to A the area is scanned clockwise and the machine is in motoring mode. Fig. 5 shows six representative trajectories. Along the trajectories 3 and 6 the rotor is static and mechanical energy is zero. Along 3 Electrical energy is stored as magnetic energy in the machine and the opposite applies to 6.

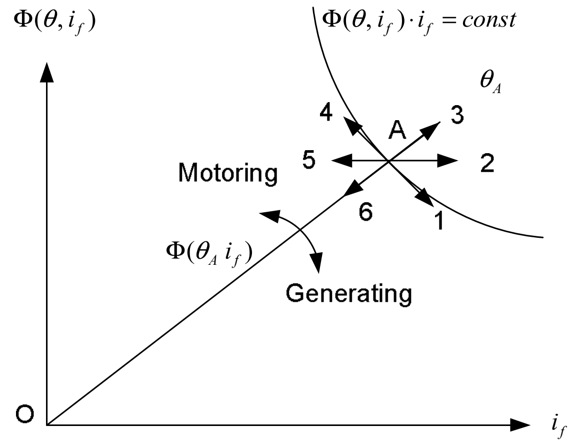

Fig.5. Directions of six representative trajectories. Trajectories 1 and 2 are generating and 4 and 5 are motoring. Trajectory 3 stores magnetic energy and 6 returns magnetic energy.

TABLE I
ENERGY FLOW ALONG TRAJECTORIES

Electrical energy $d\Phi(\omega t, i_f) \cdot i_f$	$L_f(\theta, i_f) \cdot di_f - d\Phi(\theta, i_f)$		
	> 0	$= 0$	< 0
> 0		Electric Magnetic 3	Mechanic Electric 4
$= 0$	Mechanic Magnetic 2		Mechanic Magnetic 5
< 0	Mechan Electric 1	Electric Magnetic 6	

Trajectories 5 and 2 do not involve electric energy transfer. Along 2, mechanical energy is transformed and stored as magnetic energy and the opposite applies to 5. Trajectories 4 and 1 do not involve magnetic energy. Along 1, mechanical energy is transformed into electrical energy and the opposite along 4. Table I shows the energy flows associated to the trajectories shown in Fig. 5. They have been arranged taking (2) and (3) as criteria.
Among these main trajectories there may be many others that involve ternary combinations of energy transformations. Fig. 6 shows them graphically
In the linear case, Fig. 7 shows a typical shape of the inductance profile $L_f(\theta = \omega t)$ when the generator is running at speed ω.
To start the resonant oscillations the machine will rotate at speed corresponding to a frequency between

$$\frac{1}{2 \cdot \pi \sqrt{L_{max} C}} < f < \frac{1}{2 \cdot \pi \sqrt{L_{min} C}} \tag{4}$$

The residual flux is able to excite the resonance between the phase inductance and the capacitor. As far as energy is pumped to the circuit the energy stored results in

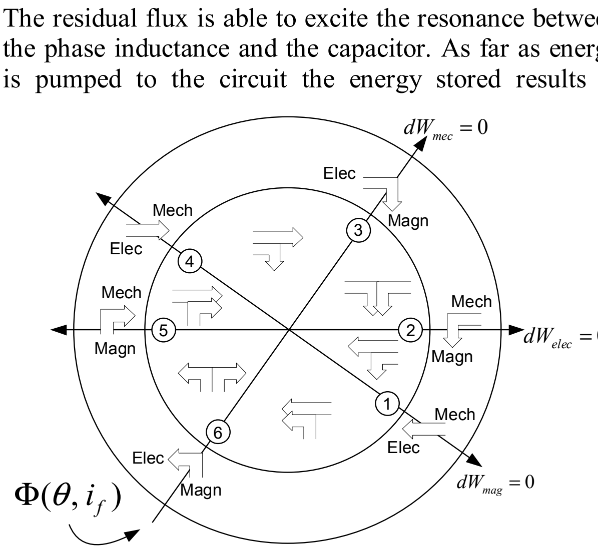

Fig. 6. Trajectories showing the energy flow assuming a linear $\Phi(\theta, i_f)$ characteristic

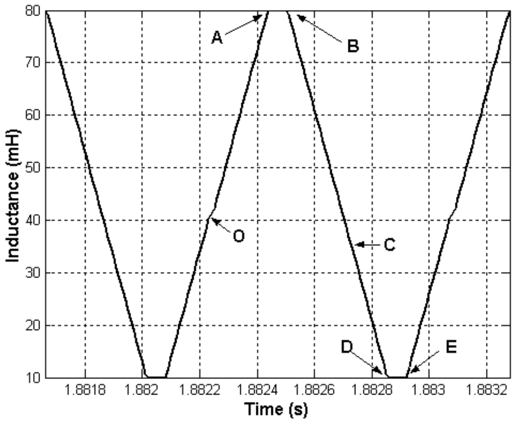

Fig. 7 Hypothetical phase inductance profile with the generator running at 32 turns/s. The characteristic points O to E are explained in text.

higher voltage and current that should be limited by feeding a load. As the pumping of energy is achieved every $L_f(\omega t)$ inductance profile period and the resonant circuit achieves symmetric alternative energy states, (corresponding to U_c positive and negative) the oscillating frequency obtained is half of what $L_f(\omega t)$ inductance profile has. For example, if the rotor speed is 3000 rpm and the motor has one phase and two poles, as in Fig. 2, then the angular speed is 50 turn per second (3000rpm/60). The energy is pumped two times per turn. Each energy stroke pumps a half cycle. Thus, the oscillating frequency is 50Hz (50 turns per second*2 strokes/2 half cycles per oscillating period).

B. Nonlinear case

In the nonlinear case, the condition for generating mode is given as

$$l_f(\theta, i_f) \cdot di_f - d\Phi(\theta, i_f) < 0 \tag{5}$$

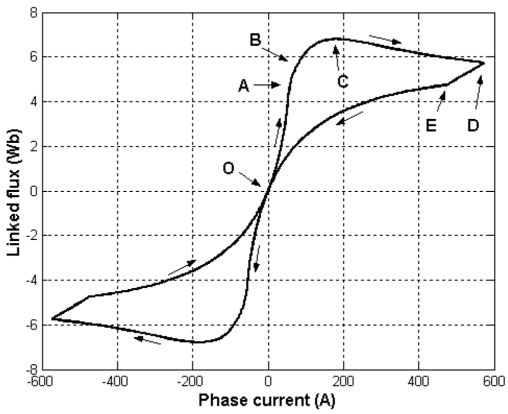

Fig. 8 Phase flux linked versus phase current. Area enclosed represents the energy generated every cycle. The characteristic points A to E are explained in text.

Where $l_f(\theta, i_f)$ is the local derivative at point A.

$$l_f(\theta, i_f) = \left. \frac{\partial \Phi(\theta, i_f)}{\partial i_f} \right|_{\theta = const} \tag{6}$$

Table 1 and Fig. 6 are essentially the same for the nonlinear case. However, line 6-3 in Fig. 6 does not belong to the magnetic characteristic as in the linear case. Only the centre of Fig. 6 belongs to the nonlinear magnetic curve. Line 6-3 is tangent to it in the central point origin of trajectories.

4. Working zones on a cyclic trajectory

The working zones along a single cycle of AC self-excited SR generator are illustrated by an example. It is assumed a single phase SR generator as depicted in Fig. 2 having a hypothetical inductance profile, when running at 32 turns/s (32Hz), as in Fig. 7. Fig. 8 shows half-cycle of the phase flux linked as a function of phase current. The enclosed area described by every turn of the generator represents the electrical energy generated per cycle. It is given by

$$E_e = \oint i_f \cdot d\Psi \tag{7}$$

The whole cycle splits into two identical half-cycles. Considering the upper half-cycle, in O the phase current and the flux state is cero. Point C represents the maximum flux state of the machine. It is reached when the capacitor voltage is close the zero. Using (1), this condition is achieved when

$$U_c - R_f \cdot i_f = \frac{d\Phi(\theta, i_f)}{dt} = 0$$
$$\Rightarrow \quad U_c \simeq 0, if\ R_f \cdot i_f \simeq 0 \tag{8}$$

A half-cycle is split in several trajectories.

A. Trajectory OABC

From O to C the machine takes energy from the capacitor. The energy provided by the capacitor is represented by

$$Eelec_{O-C} = \int_O^C i_f \cdot d\Psi \quad \text{(Through OABC)} \tag{9}$$

This trajectory can be split into O-A, A-B and B-C. From O to A the magnetic curve scans counter clockwise meaning that the machine is in the motoring mode. The machine is between directions 4 and 3 shown in Fig 6. It can be observed in Fig. 8 that the magnetic energy stored in A is lower than the electric energy taken by the machine along the trajectory O-A. This is detailed in Fig. 9 where dashed lines have been added. Lines O-A and O-E have slopes that represent the maximum and minimum of phase inductance, respectively.
The magnetic energy stored in A is

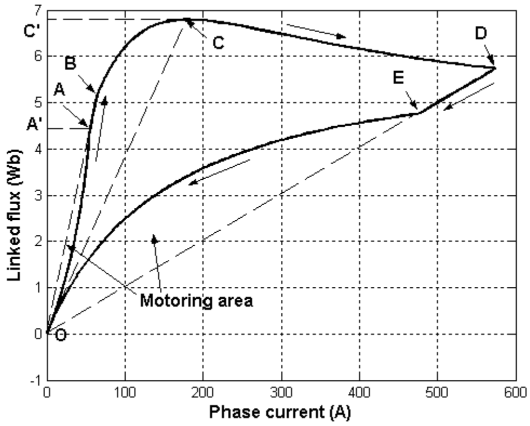

Fig. 9 Detail of characteristic points. Slopes of dashed lines CD and CB represent maximum and minimum of phase inductance.

$$Emag_A = Area\ OAA' \tag{10}$$

The electric energy absorbed by the generator from the capacitor is

$$Eelec_{O-A} = \int_O^A i_f \cdot d\Psi \quad \text{(Through curve O-A)} \tag{11}$$

The mechanical energy developed functioning as a motor in interval O-A is

$$Emec_{O-A} = Eelec_{O-A} - Emag_A \tag{12}$$

The energy in motoring mode is represented in Fig. 9 as the small area enclosed between O and A. This energy will accelerate the machine. It is a small area compared to the enclosed area O-A-B-C-D-E-O.

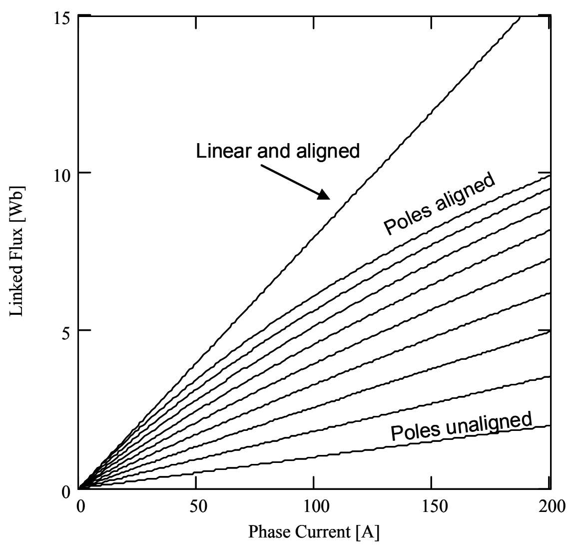

Fig. 10. Nonlinear curves of linked flux versus current using position as parameter and under nonlinear. Upper line is the linear case.

From A to B the magnetic curve does not scan area. The electric energy supplied by the capacitor is stored as magnetic energy. During this path the phase inductance remains constant at its highest value. The direction followed in Fig 6 is along 3.

From B to C, the magnetic curve scans clockwise and the machine is in generating mode. As (7) is positive, both electrical and mechanical energy is stored as magnetic energy. The direction followed in Fig 6 is between 3 and 2.

The mechanical energy obtained from the mover is,

$$\begin{aligned} &Emover = Emag_C - Eelec_{O-A-B-C} \quad where \\ &Emag_E = Area\ OCC' \end{aligned} \tag{13}$$

B. Trajectory C-D

Once the point C is reached, the machine is generating along the trajectory C-D-E-O. Although from C to O the linked phase flux is reducing, the stored magnetic energy is increasing being the highest at point D. The direction followed in Fig 6 is between 2 and 1.

C. Trajectory D-E

Between points D and E the inductance is minimum, the rotor position is close to unaligned. The inductance is constant and equal to $L_{\min}$. As E-D is aligned to the origin of co-ordinates, the electrical energy produced only comes from the stored magnetic energy. The direction followed in Fig 6 is along 6.

D. Trajectory E-O

From E to O phase current and flux linked is reduced to cero. As the curve E-O is upside the dashed line E-O the magnetic curve scans counter clockwise and the machine is in motoring mode. The recovered electrical energy is less than the stored magnetic energy; the difference is mechanical energy that the machine returns to the main mover. The direction followed in Fig 6 is between 6 and 5. The machine simultaneously generates electrical energy to the circuit and returns mechanical energy to the main mover. The electrical energy is shared by the capacitor and the load.

5. Influence of saturation on the cyclic trajectory

To show the influence of nonlinearities as saturation, the B-H magnetic curve has been supposed non linear. Fig. 10 represents the linked flux versus phase current and angular position used in the simulations. The nonlinear magnetic characteristic has been introduced by a current dependency on the inductance. It has been added the curve of the linear case for comparison. To compare the results the peak of phase linked flux has been maintained constant to nominal value of 6.76Wb. Fig. 11 shows both linear and nonlinear trajectories. It shows that saturation

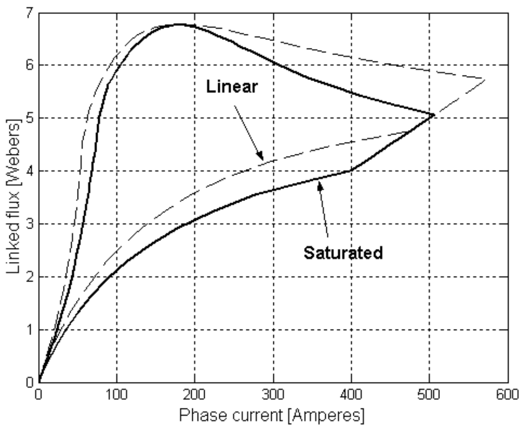

Fig. 11 Comparison of linked flux versus phase current for the linear (dashed) and nonlinear (solid) cases. Capacitor voltage is 1000Vrms in both cases. Saturation reduces the peak current and yields bigger enclosed area.

has reduced the current peak and yielded larger enclosed area.

6. Voltage quality and generated power

Fig. 12 and 13 show the main variables of the machine. The voltage quality has been stated by the THD. When compared with the linear case current peak is 11.5% less (Fig. 11) and THD is 16.09% (Fig. 13), better than the 18.4% of the linear case (not shown). The instantaneous power is pulsating although the capacitor stores and smoothes it. The third harmonic can be cancelled in three-phase systems. Most of power is generated close to the valley of the inductance profile on the negative slope of the inductance profile.

7. Conclusion

It has been systematically shown the different working

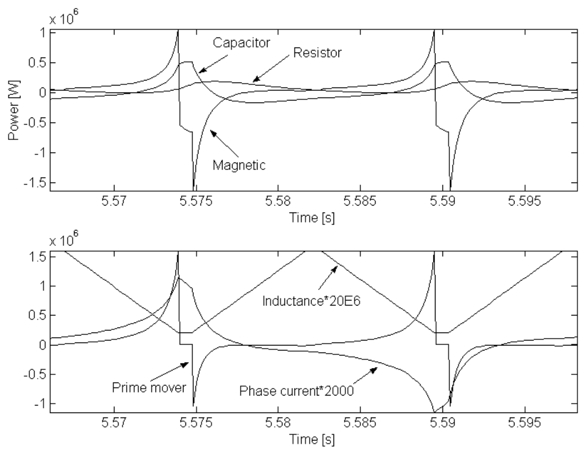

Fig. 12 Non linear case. Upper, instantaneous power in capacitor, load resistor and stored as magnetic. Lower, inductance profile, phase current and instantaneous mechanical power from the prime mover.

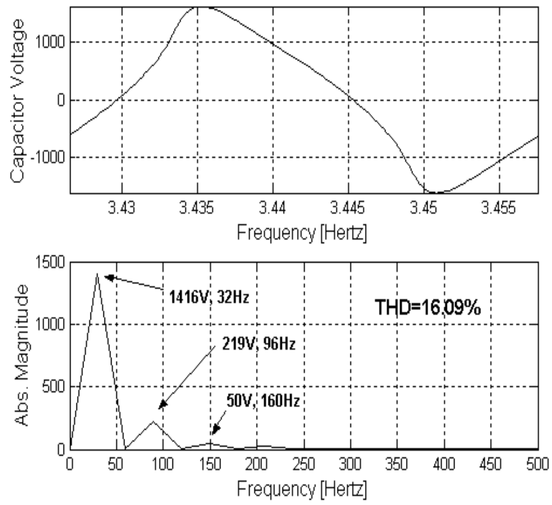

Fig. 13 Harmonic contents of load voltage when saturation is considered. The total harmonic distortion is 16.09% being better than the linear case

zones of a self-excited SR generator and the corresponding energy transformations. Then, linear and nonlinear differences are outlined. Performances are maintained under nonlinear magnetic characteristic. Third harmonic voltage can be cancelled in three-phase systems and can be applied for isolated locations. Other potential use is to rectify and supply a DC bus or a battery bank in isolated locations.

Acknowledgement

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