

Analysis of the Stable Performance of Self-excited Reluctance Generators under Variable Conditions in the Load, Excitation Capacitance and Speed

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Abstract. Reluctance synchronous machines can work as self-excited generators, in isolation mode, when their rotor, driven by a prime mover, turns to a fixed speed and capacitors of the right capacity are connected between the output terminals so they can provide the necessary reactive power for self-excitation. The generator typical parameters are obtained by testing and the presented model determines the limits of stability in the steady-state operation when the excitation capacity, the turn speed or the connected load, vary.

Keywords: Reluctance Generator, Synchronous Generator, Self-excited Reluctance Generator.

1. Introduction

Reluctance synchronous generators, when self-excited, can provide the same advantages as induction generators: brushless, small size, absence of direct current supply for excitation, reduced manufacturing and maintenance costs, self protection against overloads and short circuits. In addition to this, the output voltage frequency does not depend on the load or the capacity of the connected capacitors and the required value can be obtained by regulating the prime mover speed.

2. The self-excitation phenomenon

The transformation of energy in an electric generator is stated in terms of Kirchhoff's equations, by applying the energy conservation principle. The conditions for the existence of unidirectional transformation of energy in single winding generators are summed up in the following two conditions: The self-inductance must be a periodic function of the rotor turning angle, in such a way that the instantaneous electromagnetic torque and the average torque, in a cycle, must be other than zero, and the rotor must be toothed [4].

When there is a residual magnetism in the machine, and the required conditions for self-excitation are present, by means of a connection of the capacitors, a current is generated which frequency is $f = \Omega \cdot Z_r / 4\pi$. (Ω = turning speed and Z_r = number of the teeth in the rotor). The work point, in both cases, depends on the load, the machine d-axis magnetisation curve, the connected capacitors capacity and the rotor speed.

3. Steady state mathematical model

Taking as a basis the General Theory of Electrical Machines, by applying Blondel's Two Reaction Theory and Park's Transformation, the vectorial equations applied to the steady state of the variable reluctance synchronous generators are obtained:

$$\bar{V} + R_a \bar{I}_a + jX_d \bar{I}_d + jX_q \bar{I}_q = 0 \quad (1)$$

$$\bar{I}_a = \bar{I}_c + \bar{I}_l \quad (2)$$

$$\bar{V} = X_c \bar{I}_c = Z \bar{I}_l \quad (3)$$

The equation (1) constitutes a particular case of the steady state equations of salient pole conventional alternator with peculiarity of $E_0 = 0$.

The generator must work in the saturation zone in order to achieve the self-excitation. It is assumed that q-axis saturation is negligible, therefore X_q is constant. For this reason, X_d saturated is unknown. The parameters R_a , X_q and X_d non saturated can be experimentally obtained [4]. Once Ω , C and Z are known, we can obtain the power angle δ and X_d saturated value.

4. Generator performance under variable conditions

When performing under variable speed, it will be assumed that the reactances vary linearly with the frequency. Therefore, if $a = f / f_{base}$, X , X_d , X_q and X_c are substituted for aX , aX_d , aX_q and $(1/a)X_c = bX_c$. The equations resulting from δ and X_d are:

$$tg\delta = \frac{X_c(RX_q - R_aX) + R_a(R^2 + a^2X^2)}{X_cb[RR_a + a^2XX_q + (R^2 + a^2X^2)] - aX_q(R^2 + a^2X^2)} \quad (4)$$

$$aX_d = \frac{tg\delta(a^2R_aX^2 + R^2R_a - R_aXX_c) + bR^2X_c + aX^2X_c + bRR_aX_c}{R^2 + a^2X^2 - XX_c - bRX_c tg\delta} \quad (5)$$

The expression of the output voltage is derived from the phasor diagram, resulting:

$$V = I_d \left[\frac{X_c \sqrt{(R^2 + a^2X^2)}}{a\sqrt{(R^2 + a^2X^2)} \cos\delta - X_c \sin(\phi + \delta)} \right] \quad (6)$$

In order to guarantee self excitation and stable operation of reluctance generators, the following must be satisfied [3]:

$$\begin{aligned} 0 < \delta < \delta_{po} \\ 0 < X_d < X_0 \end{aligned} \quad (7)$$

δ_{po} = power angle in the pull out torque and $X_0 = X_d$ no saturated value.

4.1 Variable excitation capacitance

Curves $X_d = X_d(C)$ and $\delta = \delta(C)$, for Ω and Z constants, are obtained and represented. When substituting X_d for X_0 in (5), two roots are obtained: C_1 and C_2 . Curve $X_d(C)$ presents a minimum for C_m . Curve $\delta(C)$ is increasing and verifies $\delta = \delta_{po}$ for $C = C_m$. There is an value for "a" from which the roots C_1 and C_2 are imaginary. This value is the "cut speed" from which the self excitation is not possible [4]. Since $C_1 < C_m < C_2$, it means that the range for a stable operation is: $C_1 < C < C_m$. Curve $V = V(C)$ is represented in this range.

4.2 Variable speed

Curves $X_d = X_d(a)$ and $\delta = \delta(a)$, for C and Z constants, are presented. When substituting X_d for X_0 in (5), two roots are obtained: a_1 and a_2 . Curve $X_d(a)$ presents a minimum for a_m . Curve $\delta(a)$ is increasing and verifies $\delta = \delta_{po}$ for $a = a_m$. Since $a_1 < a_m < a_2$, it means that the range for a stable operation is: $a_1 < a < a_m$. Curve $V = V(a)$ is represented in this range.

4.3 Variable load

Curves $X_d = X_d(Z)$ and $\delta = \delta(Z)$, for C and Ω constants and a fixed value for the load power factor, are presented. X_d and δ decrease when Z increases. Z has got a minimum value which makes $X_d = X_0$ and $\delta = \delta_0$. Therefore, the stable operation range is: $Z > Z_{min}$. The value for Z_{min} depends on the load power factor. Curves $V = V(Z)$ and $V = V(I_l)$ are represented in this range.

5. Conclusions

This model allows us to obtain the reluctance generator operation margins for any value for C , Ω and Z and determine the value for the output voltage (V) according to the variation of one of these parameters, keeping the other two constants. In order to make the self excitation and stable operation possible, the range of the operation will be limited by: $C_{min} < C < C_{max}$; $a_{min} < a < a_{max}$; $Z > Z_{min}$. The machine cannot operate beyond these limiting values.

In order to verify the validity of the model, an universal machine for didactic applications shaped as three phase reluctance generator has been used [4].

References

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