PERFORMANCE COMPARISON OF THE CAGE AND CAGELESS SELF-EXCITED TWO-PHASE RELUCTANCE GENERATOR

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Abstract

This study theoretically compared the performance of a self-excited two-phase reluctance generator (SETPRG) with cage and without cage. The modeling of the two machines was detailed to accommodate conditions of unbalanced stator winding, excitation capacitor, or/and load. It was observed that machines without cage build-up voltage, and recovers from short-circuit at the terminals faster than machines with cage. However, they have much reduced power capacity than machines with cage.

Keywords: SETPRG, Two-Phase, Cage.

1. Introduction

Many research works has been completed in autonomous generating units in an attempt to maximize non-conventional sources of electric power. In particular, the reluctance generator has gained much attention and wide acceptance as a reliable autonomous generating unit. It offers output voltages with constant frequency independent of the load conditions, requires no dc supply for excitation, and it is rugged. In comparison with its equivalent induction generator, although it offers less output power, it is cheaper and requires minimum maintenance. Moreover, it does not generate at a leading power factor and it could well develop its own excitation current (Allam, 2006).

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Many journals and conference proceedings are replete with studies on the three-phase and single-phase reluctance generators. A two-phase reluctance generator was reported by Obe and Onwuka (2011). By two-phase it is implied that it can supply single phase loads from the two-stator terminals, with a phase difference of 90°. Its attractions were also mentioned.

In particular, the stator of the machine that was studied herein was adapted from the work of Onwuka and Uma (2015). Self-excitation is achieved using capacitors connected across the load. Self-excitation using shunt capacitors is possible if permanent magnetism exists in the machine core, and also depends on magnetic saturation of the core. Obe and Anih (2010) observed that
the removal of the damper cage of a synchronous reluctance machine allows for more modifications of the rotor geometry to reduce the quadrature axis flux path, and hence the quadrature axis reactance, which improves the machine performance. Hoeijmakers (2004) suggested modeling techniques for synchronous machines without damper winding. It is therefore the intention of this article to compare the performance of the two-phase reluctance generator with damper windings (cage) and without damper windings (cageless).

2. Model of the SETPRG

The model of SETPRG presented hereunder uses the rotor rotating reference frame as advanced by Krause (2002). This is the most convenient way to deal with the time varying inductances of the machine. Although synchronous, reluctance generators have no field windings.

Two damper windings are considered on the rotor, one in each of the q- and d-axes. The stator winding is arranged as in figure 1. It is also considered that the stator windings may or may not be identical, the excitation capacitors may or may not be equal, and the load on either phase may differ.

Thus, when the machine equations as obtained from figure 1 are transformed to the q-d rotor reference frame, the voltage equations of the machine becomes:

\[ V_{qs} = -R_{qs} i_{qs} - R_{qds} i_{ds} + \omega_r \lambda_{ds} + p \lambda_{qs} \]  
\[ V_{ds} = -R_{qds} i_{qs} - R_{ds} i_{ds} - \omega_r \lambda_{q} + p \lambda_{d} \]  
\[ V_{kq} = n_{kq} i_{kq} + p \lambda_{kq} \]  
\[ V_{kd} = n_{kd} i_{kd} + p \lambda_{kd} \]

Where
\[ R_{qs} = R_1 + R_2 \cos 2\theta_r \]  \hspace{1cm} (5)

\[ R_{ds} = R_1 - R_2 \cos 2\theta_r \]  \hspace{1cm} (6)

\[ R_{qd} = R_2 \sin 2\theta_r \]  \hspace{1cm} (7)

\[ R_1 = \frac{1}{2} (r_{as} + r_{bs}) \]  \hspace{1cm} (8)

\[ R_1 = \frac{1}{2} (r_{as} - r_{bs}) \]  \hspace{1cm} (9)

\( r_{as} \) and \( r_{bs} \) are the a- and b-phase winding resistances respectively. The flux linkages appearing in (1) - (4) are defined as follows:

\[
\begin{bmatrix}
\lambda_{qs} \\
\lambda_{ds} \\
\lambda_{kq} \\
\lambda_{kd}
\end{bmatrix} =
\begin{bmatrix}
L_{qs} & 0 & L_{mq} & 0 \\
0 & L_{ds} & 0 & L_{md} \\
L_{mq} & 0 & L_{kq} & 0 \\
0 & L_{md} & 0 & L_{kd}
\end{bmatrix}
\begin{bmatrix}
i_{qs} \\
i_{ds} \\
i_{kq} \\
i_{kd}
\end{bmatrix}
\]  \hspace{1cm} (10)

For the purpose of computer simulation, the current expressions can easily be obtained from (10).

The contribution of the shunt capacitors is modeled as follows:

\[ pQ_{qs} = i_{qs} - i_{qi} - \omega_r Q_{ds} \]  \hspace{1cm} (11)

\[ pQ_{ds} = i_{ds} - i_{dl} + \omega_r Q_{qs} \]  \hspace{1cm} (12)

Where

\[ Q_{qs} = C_q V_{qs} + C_{qd} V_{ds} \]  \hspace{1cm} (13)

\[ Q_{qs} = C_{qd} V_{qs} + C_d V_{ds} \]  \hspace{1cm} (14)

\[ C_q = C_1 + C_2 \cos 2\theta_r \]  \hspace{1cm} (15)

\[ C_d = C_1 - C_2 \cos 2\theta_r \]  \hspace{1cm} (16)

\[ C_{qds} = C_2 \sin 2\theta_r \]  \hspace{1cm} (17)

\[ C_1 = \frac{1}{2} (C_{sha} + C_{shb}) \]  \hspace{1cm} (18)

\[ C_2 = \frac{1}{2} (C_{sha} - C_{shb}) \]  \hspace{1cm} (19)

The load is defined by the following equations.
\[ i_{q1} = R_{q1} V_{qs} + R_{qdl} V_{ds} - \omega_r S_2 - pS_q \] (20)

\[ i_{d1} = R_{qdl} V_{qs} + R_{d1} V_{ds} + \omega_r S_q - pS_d \] (21)

Where

\[ R_{q1} = r_1 + r_2 \cos 2\theta_r \] (22)

\[ R_{d1} = r_1 - r_2 \cos 2\theta_r \] (23)

\[ R_{qdl} = r_2 \sin 2\theta_r \] (24)

\[ r_1 = \frac{1}{2} \left( \frac{1}{\delta_{la}} + \frac{1}{R_{lb}} \right) \] (25)

\[ r_2 = \frac{1}{2} \left( \frac{1}{\delta_{la}} - \frac{1}{R_{lb}} \right) \] (26)

\[
\begin{bmatrix}
S_q \\
S_d
\end{bmatrix} =
\begin{bmatrix}
t_1 + t_2 \cos 2\theta_r & t_2 \sin 2\theta_r \\
t_2 \sin 2\theta_r & t_1 - t_2 \cos 2\theta_r
\end{bmatrix}
\begin{bmatrix}
i_{q1} \\
i_{d1}
\end{bmatrix}
\] (27)

\[ t_1 = \frac{1}{2} \left( \frac{\delta_{la}}{\delta_{la}} + \frac{\delta_{lb}}{R_{lb}} \right) \] (28)

\[ t_2 = \frac{1}{2} \left( \frac{\delta_{la}}{\delta_{la}} - \frac{\delta_{lb}}{R_{lb}} \right) \] (29)

The mechanical (\( p\omega_r \)) and torque (\( T_e \)) equations are defined by the following equations, in order:

\[ p\omega_r = \frac{p}{2j} (T_l - T_e) \] (30)

\[ T_e = \frac{p}{2} \left( \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \right) \] (31)

Where \( T_l \) is the mechanical torque input to the rotor shaft in Nm units, \( P \) is the number of pole pairs, \( J \) is the combined inertia of the rotor and the driving shaft.

Similarly, the power developed by the generator is expressed as follows:

\[ S = (V_{qs} i_{qs} + V_{ds} i_{ds}) + j (V_{qs} i_{ds} - V_{ds} i_{qs}) \] (32)

The saturation of the core was modeled along the d-axis only as suggested by Allam et al (2006) and Obe and Anih (2010), by defining the stator d-axis inductance of this particular machine as:
\[ L_d = 1.4393\lambda_m^4 - 2.1195\lambda_m^3 + 0.6472\lambda_m^2 + 0.0808\lambda_m + 0.0938 \]

(33)

Where \(\lambda_m = \sqrt{\lambda_{mq}^2 + \lambda_{md}^2} \)  

(34)

\[ \lambda_{mq} = \frac{\frac{\lambda_{dq}}{L_{dq}} + \frac{\lambda_{dq}}{L_{dq}}} {\frac{1}{L_{dq}} + \frac{1}{L_{dq}}} \]

(35)

\[ \lambda_{md} = \frac{\frac{\lambda_{dq}}{L_{dq}} + \frac{\lambda_{dq}}{L_{dq}}} {\frac{1}{L_{dq}} + \frac{1}{L_{dq}}} \]

(36)

With the above equations, the SETPRG is completely modeled for the case with damper windings, in such a manner that accommodates unbalanced loading at the terminals.

For the case where the damper windings are absent (cageless), the rotor currents will be zero, requiring modifications only in equations (3), (4), and (10).

One important assumption made in this comparison is that the remanent magnetism in the machine core is 0.005T, along the d-axis.

3. Simulation

MATLAB and SIMULINK (2007) is the simulation tool used in this study. Equations 1-36 were implemented using the embedded MATLAB function in the SIMULINK environment. Results were sent to the workplace from where they were plotted with convenient axes.

4. Results and Discussions

4.1 Excitation and voltage build-up

It is observed that there is a limit of capacitor value beyond which excitation fails and the voltage does not build-up. At no-load, for the SETPRG with cage, this limit is \(108\mu F \leq C_{sh} \leq 132.45\mu F\). At no-load, for the SETPRG without cage, this limit is \(108.29\mu F \leq C_{sh} \leq 112.79\mu F\). It is however observed that as a balanced load applied to the terminals increases, these limits also increase. The limiting factor in selecting the shunt capacitor rating will be the rated stator current. These limits were gotten by continuously adjusting the excitation capacitors until build-up begins to fail (downward adjustment) or the voltage fails to converge (upward adjustment).

For ease of comparison, the same value of excitation capacitor is selected for the two machines in this study, that is, \(110\mu F\).

One of the implications of these limits is that the cageless machine cannot develop as much power as the machine with cage.
The voltage build-ups of the two machines were simulated, and the results presented in figure 2. On account of the absence of rotor conductors, the time constant of the cageless machine is less than that of the machine with cage. This accounts for the more rapid voltage build-up of the former compared to the later. It will be on point to mention that a few other factors that affect the build-up time include the remanent magnetism in the core, the capacitor size, and the applied load.

![Graph 2(a): No-load voltage build-up with cage](image1)

![Graph 2(b): No-load Voltage build-up without cage](image2)

4.2 Load Power Factor Considerations

The load power factor does not affect the size of the excitation capacitor. The generator with cage is able to generate at lower power factors for a constant load resistance than the generator without cage. This study was performed with a constant load resistance of 70Ω and excitation capacitor of 155µF, and the load power factors varied, while observing the build-up of the voltage and other machine variables. If the two generators are run-up with load at varying power factors, it will be observed that the terminal voltage of the two generators have the same magnitude. However, below power factors of 0.76, the generator without cage could not generate, while the generator with cage generated even below 0.60 load power factor.
4.3 Load Characteristics

The load characteristics of both machine was also observed at various power factors at a fixed excitation capacitor of 110µF, and represented in figure 3 for easy comparison. This was achieved by gradually loading the generators from no-load to full load until each machine reaches pull-out. Obviously, the machine with cage can handle more power than the machine without cage.

4.4 Transient Loss of Load

Another study performed on the two machines was their response to sudden addition and removal of load. For this study, only the upper envelope of the terminal voltage was considered. A constant load resistance of 70Ω was applied to each generator at t=5sec, and removed at t=7.5 sec. The voltage characteristic was observed and represented in figure 4.

More transients were observed in the case of the generator without cage than in the generator with cage, a clear influence of the rotor windings.
The rotor currents for the case of power factor of 0.99 are shown in figure 5. They act to damp out oscillations due to any change introduced to the system.

An extension of this exercise was to observe the response of the two machines to a sudden short circuit at their terminals, which is cleared early enough to avoid total voltage collapse.

In this study, the machines were started on no-load, a short circuit applied at t=5sec for a period of 0.1 seconds. The results are shown in figure 6. Again, the generator without cage re-built its voltage more rapidly than the one with cage, on account of smaller time constant due to the absence of rotor time constants.
Fig. 5: The q-axis and d-axis rotor currents

5. Conclusion

It is clear from the studies made that:

i. The absence of rotor windings does not prevent the voltage build-up of the SETPRG, as long as a remanent magnetism is available in the core.
ii. Voltage build-up of the machine is faster without rotor windings. This is so because the absence of rotor currents means that only the stator time constant is present.

![Graph showing voltage response to sudden short circuit at the terminals.](image)

**Fig. 6:** Voltage response to sudden short circuit at the terminals, (a) for machine with cage, (b) for machine without cage.

iii. Power handling capacity of the machine without rotor winding is significantly less than that with rotor windings. The presence of the rotor windings enables the machine to develop more electromagnetic torque against the applied mechanical torque. This also accounts for the higher values of excitation capacitor required by the machine with cage.

iv. In both cases, the machine is able to recover from the sudden addition and loss of load, as well as from a short circuit applied to the terminals for a short time. The rate of recovery is faster for the case of machine without cage. However, more transients occur at every change in the load condition with the same machine, than it is with the machine with cage.

Other investigations can be made on this subject such as the effect of unbalanced loading at the terminals, excitation with different capacitor values on the two phases, and the variation of terminal voltage with load power factor.

**References**


