Effect of the Stator Mutual Leakage Reactance of Dual Stator Induction Generator

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Abstract—this paper presents a mathematical model of dual stator induction generator (DSIG) for analysis of its transient behavior for self-excited induction generator. The induction machine has two sets of three-phase stator windings spatially shifted by 30 electrical degrees. In the analytical model, impact of common mutual leakage reactance between the two three-phase stator winding sets has been considered with three cases. The proposed steady state generalized model of DSIG self-excited dispenses with tedious work of segregating real and imaginary components of the complex impedance of dual stator induction generator for deriving the specific models for each operating mode. Predictions of various electrical characteristics have shown the importance of taking into account the mutual leakage fluxes in the DSIG modeling, especially in static operation. Paper also discusses the applicability of DSIG for supplying two individual loads by presenting the results of simulation and experimental study of steady-state behavior under various operating conditions.

Index Terms—dual stator induction generator, self excited induction generator, mutual leakage reactance, experimental study of steady-state

I. INTRODUCTION

Self-excitation phenomenon in multi-phase induction machines, although known for more than half a century [1], [2], is still a subject of considerable attention. The interest in this topic is sustained primarily due to application of dual stator self-excited induction generators in isolated power systems. A source of reactive power, that is required for self-excitation and subsequent generating operation, can be any of the numerous types of static reactive power compensators [3].

Physical background of the self-excitation process has been described in considerable depth in Ref. [4]. The initiation of the excitation in the induction machine can be viewed as a response of the resonant circuit, that is composed of the machine and the variable capacitor bank connected to its terminals.

The investigations spread over the last two decades indicate the technical and economic viability of using the number of phase higher than three in transmission [4], multi-phase machines in general [5] and induction machines [6]-[9] in particular. The research in this area is still in its infancy, yet some extremely important findings have been reported in the literature indicating general feasibility of multi-phase systems.

Recently, Singh and Al, have presented the modeling and analysis of six-phase SEIG where the effect of common mutual leakage reactance between the two three-phase stator winding sets has been included. In [10]-[14], performance evaluation of simple shunt and series compensated (short-shunt) six-phase SEIG is discussed showing its practical feasibility, where as Singh deals with the steady-state modeling and analysis of six-phase SEIG. Similarly, Tessarolo in [15] proved the impact of leakage inducances on multi-phase machine performance, especially in PWM inverter-supplied synchronous motors by using finite element techniques.

However, the study of the effect of the common mutual leakage reactance in the self-excited dual stator induction generator steady-state performance is nearly nonexistent in the literature. For this purpose, the aim of this paper is therefore to report on results of an extensive experimental investigation of a SEIG operation. Self-excitation under no-load conditions, with capacitor bank connected in star loading of the generator is investigated. The attention is focused at the impact of the common mutual leakage reactance between the two three-phase stator winding sets with this three cases: (a) mutual leakage reactance \((X_{sm})\) is correctly included, (b) \(X_{sm}\) is considered with self leakage reactance \(X_{sr}\) and (c) \(X_{sm}\) is ignored. Experimentations were also carried out to judge the performance of the dual stator SEIG including loading and unloading characteristic. Very good correlation between theatricals and experimental results.

A common type of multiphase machine is the dual stator induction machine (DSIM), where two sets of three-phase windings, spatially phase shifted by an angle \(\alpha\), share a common stator magnetic core.

II. STEADY STATE ANALYSIS

Fig. 1 shows per phase equivalent circuit of a dual stator SEIG under resistive load. Where \(R_1, R_2\)
Model 1 with (\(\theta_1, \theta_2\)) = (0, 1), corresponds to the case where the stator mutual leakage inductance is correctly included.

In model 2 with (\(\theta_1, \theta_2\)) = (0, 1); \(X_m\), is also considered but as a self leakage impedance.

If both (\(\theta_1, \theta_2\)) are null, the mutual leakage impedance is ignored in the modeling process.

At note “A” in Fig. 1, the relation between \(\bar{T}_{s1}, \bar{T}_{s2}\) and \(\bar{T}_s\) can be written as:

\[
\bar{T}_s = \bar{T}_{s1} + \bar{T}_{s2}
\]

(2)

When the two sets of stator three-phase windings are identical, then we can write:

\[
\bar{T}_{s1} = \bar{T}_{s2} = \frac{\bar{T}_s}{2}
\]

(3)

At note “A1” in Fig. 2, the relation between \(\bar{T}_{sl1}, \bar{T}_{sl2}\) and \(\bar{T}_{sl}\), can be written as:

\[
\bar{T}_{sl} = \bar{T}_{sl1} + \bar{T}_{sl2}
\]

(4)

where:

\[
\begin{bmatrix}
\bar{T}_{c1} \\
\bar{T}_{sl1} \\
\bar{T}_{sl1}
\end{bmatrix}
= V_1\begin{bmatrix}
1 & 0 & 0 \\
\frac{1}{\bar{Z}_{sl1}} & 1 & 0 \\
\frac{1}{\bar{Z}_{c1}} & 0 & 1
\end{bmatrix}
\]

(5)

Similarly, the same calculation procedures are adopted to obtain the stator, excitation and load current for the second stator (\(\bar{T}_{s2}, \bar{T}_{sl2}, \bar{T}_{c2}\)). In order to simplify the study, the following per phase circuit based on impedance analysis are considered, Fig. 2.

where, \(\bar{Z}_s, \bar{Z}_c, \bar{Z}_p, \bar{Z}_m, \) and \(\bar{V}_r\) can be represented by using the equivalent circuit as follows:

\[
\begin{align*}
\bar{Z}_s &= \frac{\bar{Z}_{sl1}\bar{Z}_{sl1}}{\bar{Z}_{sl1} + \bar{Z}_{c1}} + \bar{Z}_s; \quad \bar{Z}_c = \frac{\bar{Z}_{sl1}\bar{Z}_{sl1}}{\bar{Z}_{sl1} + \bar{Z}_{c1}} + \bar{Z}_c

\bar{V}_s &= \frac{1}{\bar{Z}_{sl1}} \bar{Z}_s; \quad \bar{V}_c = \frac{1}{\bar{Z}_c}; \quad \bar{V}_r = \frac{1}{\bar{Z}_r}\bar{Z}_c + \frac{R}{g}
\end{align*}
\]

(6)

### Table I. Values of (\(\theta_1, \theta_2\)) for Each Model Version

<table>
<thead>
<tr>
<th>Model</th>
<th>(\theta_1)</th>
<th>(\theta_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Model 2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Model 3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table I resumes the different values taken by the pair (\(\theta_1, \theta_2\)) for each model version.
At note ‘B’ in Fig. 2, the relation between $\bar{I}_m$, $\bar{I}_s$ and $\bar{I}_r$ can be written as:

$$\bar{I}_s = \bar{I}_r + \bar{I}_m$$  \hspace{1cm} (7)

$$\begin{bmatrix} I_m \\ I_r \\ I_s \end{bmatrix} = \begin{bmatrix} 1 \\ \frac{1}{Z_m} \\ \frac{1}{Z_s} \end{bmatrix}$$ \hspace{1cm} (8)

Hence, equation (7) can be written as:

$$\bar{E} (Y_m + Y_r + Y_s) = 0$$ \hspace{1cm} (9)

Under normal operating condition, the stator voltage $\bar{E} \neq 0$. Therefore, the total admittance must be equal to zero.

$$Y_m + Y_r + Y_s = 0$$ \hspace{1cm} (10)

This implies that both the real and imaginary components of (11) should be independently zero.

$$\begin{cases} \text{Re}(\bar{O}_m + \bar{O}_r + \bar{O}_s) = 0 \\ \text{Im}(\bar{O}_m + \bar{O}_r + \bar{O}_s) = 0 \end{cases}$$ \hspace{1cm} (11)

Real (10) and Img (10) is solved by using “fzero” MATLAB function. For a given excitation capacitor and prime mover speed, the system of equation (11) has a one unknown parameter, which is the frequency $F$, [15].

Total admittance is considered here as an objective function, and the constrained function is applied to find out simultaneously the value of $F$ and $X_m$. Subsequently, we can predict the necessary parameters to evaluate the performance characteristics of the dual stator SEIG. The value of $F$ and $X_m$ is simultaneously computed for different operating condition by varying the load resistance, and keeping the speed constant at desired value or with fixed excitation capacitance.

III. COMPUTER AND EXPERIMENTAL RESULTS

Alternatively, the values of star-capacitance at a given speed to generate a particular terminal voltage can be obtained experimentally by using a variable capacitor bank.

A detailed study of steady-state performance of the dual stator SEIG indicates that for three models, self-excitation under no-load condition and loading performance under a typical resistive load are elaborated.

For simulation of no-load operation, $R_{ch1}$ and $R_{ch2}$ in the (1) are replaced by infinity. Fig. 3, Fig. 4, Fig. 5 and Fig. 6 show experimental and simulation results performed with the three cases at steady state self-excited generator operation at no-load.

Stator voltage and current curves indicate that the case 1 ($X_m$ is correctly included) is the more realistic, as expected. Another important feature is to be observed from Fig. 4 and Fig. 5, more shaft speed increases more the difference between curves relative to the different cases is decreasing.

Fig. 4 Shows, the behavior obtained from the experiment, of the output voltage as a function of speed. These curves show two areas. The first, when the voltage increases very rapidly with the speed, the corresponding points are those obtained just after the self-excitation. In the second area, voltage varies linearly with the speed to a low coefficient. This area, where the characteristics are substantially parallel, corresponds to the stable part of the dual stator generator.

Stator current per phase versus speed at no-load

FIGURE 4

Terminal voltage per phase versus speed at no-load

FIGURE 3

Stator current per phase versus speed at no-load

FIGURE 5

Stator voltage set 'I' phase 'a' (V)

Terminal voltage set 'I' phase 'a' (V)

Stator current set 'I' phase 'a' (A)

Stator current set 'I' phase 'a' (V)

Stator current set 'I' phase 'a' (A)

Stator current set 'I' phase 'a' (V)

Stator current set 'I' phase 'a' (A)

Stator current set 'I' phase 'a' (V)

Stator current set 'I' phase 'a' (A)

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Stator current set 'I' phase 'a' (V)

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Stator current set 'I' phase 'a' (V)

Stator current set 'I' phase 'a' (A)
Experimental and simulation were performed after varying resistive load using the defined three types of models. Characteristic curves shown in Fig. 7 and Fig. 8 depict the variation of terminal voltage and stator current when two winding sets are equally loaded. It is worth reminding that case 1, supposed to be the more accurate, and was also taken as a reference for any comparison.

<table>
<thead>
<tr>
<th>Terminal voltage (V)</th>
<th>Load current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 7. Terminal voltage for stator 1 with load current

Terminal voltage and machine current both start decreasing with the increase in load.

<table>
<thead>
<tr>
<th>Stator current (A)</th>
<th>Load current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 8. Stator current per phase versus load current

IV. CONCLUSIONS

In this paper, a detailed structure of dual stator self-excited induction generator (DS-SEIG) is presented. In the analytical model, the effects of common mutual leakage reactance $X_{cm}$ between the two three-phase winding sets have been discussed with three possible cases:

1) The mutual leakage reactance is correctly included.
2) The mutual leakage reactance is considered as a self leakage reactance $X_{sl}$.
3) The mutual leakage reactance is neglected.

Paper also discusses the applicability of a dual stator capacitor excited induction generator for supplying two individual three-phase loads, by presenting results of an experimental study of steady-state behavior for various operating conditions.

APPENDIX NOMENCLATURE

C1: excitation capacitance per phase with stator 1.
C2: excitation capacitance per phase with stator 2.
E: air gap voltage per phase at rated frequency F.
Is1: stator 1 current per phase.
Is2: stator 2 current per phase.
Ir: rotor current per phase, referred to stator.
Im: magnetizing current per phase.
Is: common stator current.
Rs1: stator 1 resistance per phase.
Rs2: stator 2 resistance per phase.
Rr: rotor resistance per phase, referred to stator.
V: load voltage per phase.
Xs1: stator 1 reactance per phase.
Xs2: stator 2 reactance per phase.
Xm: stator mutual leakage reactance per phase.
$X_{r}$: rotor reactance per phase, referred to stator.
$X_{1}$: capacitive reactance due to $C_1$ at rated frequency.
$X_{2}$: capacitive reactance due to $C_2$ at rated frequency.

REFERENCES

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