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Performance Evaluation of the Stator Mutual Leakage Impedance of Wind Generator Based on the Dual Stator Winding Induction Generator

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***Abstract*— this paper treats the self-excited and the steady state modelling of dual stator winding induction generator (DSWIG) by proposing three electric models. Its main objective is to study the sensitivity of the stator mutual leakage impedance on the modelling of such generator, when we used three versions of DSWIG electric models. The emphasis is placed on an extensive presentation of the effect of the stator mutual leakage impedance between two stator stars, by examining the electrical quantities. The proposed steady state generalized model of DSWIG 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. A detailed simulation and experimental investigation about various performances of self-excited dual stator induction generator is also presented in this paper**.

***Index Terms*— self excited induction generator, steady state of SEIG, mutual leakage impedance.**

I. INTRODUCTION

The next exhaustion of fossil fuels has contributed to the development of renewable energy in general and wind energy in particular [1]. Currently, wind turbines can be classified into two categories: fixed-speed and variable speed, in our case we opted for variable speed wind turbines. Indeed the latter have several advantages, namely better exploitation of wind energy, reducing torque oscillations [8].

It is well known that an induction generator may generate voltage if a capacitor is connected to its stator terminals while its rotor is driven by a prime-mover. In this case, the capacitor provides the lagging magnetizing reactive power which is necessary to establish the air-gap and this configuration is referred to as a self-excited dual stator winding induction generator (SEDSWIG). In recent years, the SEDSWIG has been increasingly used in isolated power systems employing renewable energy sources such as wind and hydro-power [3-10], due to its lower cost, brushless rotor, ruggedness, and ease of maintenance, etc. However, one of the major drawbacks of the stand-alone SEDSWIG is its poor voltage and frequency regulation. Unless the SEDSWIG is connected to a utility grid, its frequency and stator voltage are free to vary with rotor speed and load. The terminal voltage of an isolated SEIG increases considerably for a small increase in speed [11-21]. In most developing countries, unregulated wind and micro-hydro turbines are often used due to their lower cost, which renders such systems suitable only for supplying power to loads where voltage and frequency need not to be regulated.

This paper, therefore, discusses a sensitivity of mutual leakage impedance of dual stator winding self-excited induction generator (DSW-SEIG) configured to operate as a stand-alone operation mode. The generator can also supply two separate three-phase loads, which represents an additional advantage. Last but not least, outputs of the dual three-phase windings can be used. Experimental results include study of self-excitation transients with capacitor bank at each of the two three-phase windings and loading transients with independent three-phase resistive loads at each of the two three-phase winding sets have been presented.

The presence of the mutual leakage impedance between the two stars of induction generator is due to the fact their windings share the same slots, and are, therefore, mutually coupled. The mutual leakage coupling has an important effect on the harmonic coupling between the two stator winding sets and depends on the winding pitch and the displacement angle between the two stator winding sets. Nevertheless, there have been studies where the mutual leakage coupling has been neglected [20].

II. STEADY STATE MODELING

Fig.1 shows per phase equivalent circuit of a dual stator winding SEIG under resistive load. Where $R_{s1}, R_{s2}, R_r^{'}, X_{s1}, X_{s2}$, $X_{sm}, X_m, X_r^{'}, X_c, R_{ch1}, R_{ch2}$ and g represent the stator 1 and 2 resistance, rotor resistance (referred to stator), stator 1 and 2 leakage reactance, mutual leakage reactance between the two stator, magnetizing reactance, rotor leakage reactance (referred to stator), excitation capacitor reactance, load resistance and the generator slip respectively.

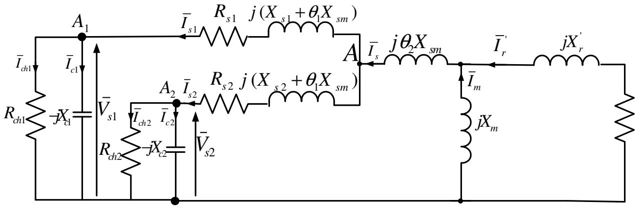

Fig. 1: Equivalent circuit of dual stator self-excited induction generator.

When the dual stator winding SEIG is driven by dc machine in which the shaft speed is maintained constant. All parameters are fixed but both X_m and g vary with the load and hence they must be taken as variables for a given load and excitation capacitance condition, [15-18]. The parameters of the equivalent circuit are given below:

$$\begin{cases} \bar{Z}_{c1} = -jX_{c1};\ \bar{Z}_{c2} = -jX_{c2} \\ \bar{Z}_{ch1} = R_{ch1};\ \ \bar{Z}_{ch2} = R_{ch2} \\ \bar{Z}_{s1} = R_{s1} + j(X_{s1} + \theta_1 X_{sm}); \\ \bar{Z}_{s2} = R_{s2} + j(X_{s2} + \theta_1 X_{sm}) \\ \bar{Z}_{sm} = j\theta_2 X_{sm} \\ \bar{Z}_r = \frac{R_r}{g} + jX_r;\ \bar{Z}_m = jX_m; \end{cases} \tag{1}$$

Table 1 resumes the different values taken by the pair (θ_1, θ_2) for each model version.

TABLE I: VALUES OF (θ_1, θ_2) FOR EACH MODEL VERSION

I	θ_1	θ_2
Model 1	0	1
Model 2	1	0
Model 3	0	0

Model 1 with $(\theta_1, \theta_2) = (0,1)$, corresponds to the case where the stator mutual leakage impedance is correctly included.

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

If both (θ_1, θ_2) are null, the mutual leakage impedance is ignored in the modeling process.

At note "A" in fig.1, the relation between $\bar{I}_{s1}, \bar{I}_{s2}$ and $\bar{I}_s$ can be written as:

$$\bar{I}_s = \bar{I}_{s1} + \bar{I}_{s2} \tag{2}$$

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

$$\bar{I}_{s1} = \bar{I}_{s2} = \frac{\bar{I}_s}{2} \tag{3}$$

At note "A$_1$" in fig.2, the relation between $\bar{I}_{ch1}, \bar{I}_{c1}$ and $\bar{I}_{s1}$ can be written as:

$$\bar{I}_{s1} = \bar{I}_{ch1} + \bar{I}_{c1} \tag{4}$$

Where:

$$\begin{bmatrix} \bar{I}_{c1} \\ \bar{I}_{ch1} \\ \bar{I}_{s1} \end{bmatrix} = \bar{V}_{s1} \begin{bmatrix} \frac{1}{\bar{Z}_{c1}} \\ \frac{1}{\bar{Z}_{ch1}} \\ -\frac{1}{\bar{Z}_{s1}} \end{bmatrix} \tag{5}$$

Similarly, the same calculation procedures are adopted to obtain the stator, excitation and load current for the second stator $(\bar{I}_{s2}, \bar{I}_{ch2}, \bar{I}_{c2})$. In order to simplify the study, the following per phase circuit based on impedance analysis are considered, fig. 2.

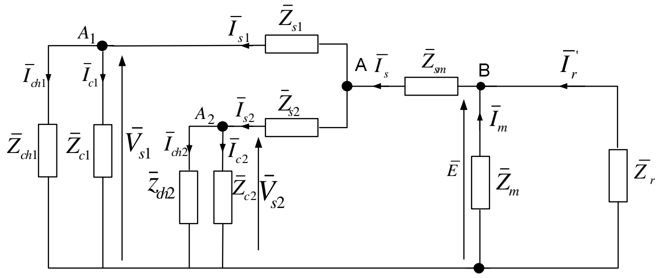

Fig. 2: Simple per phase equivalent circuit of dual stator SEIG.

Where, $\bar{Z}_1, \bar{Z}_2, \bar{Y}_s, \bar{Y}_m$ and $\bar{Y}_r$ can be represented by using the equivalent circuit as follows:

$$\begin{cases} \overline{Z}_1 = \dfrac{\overline{Z}_{ch1}\overline{Z}_{c1}}{\overline{Z}_{ch1}+\overline{Z}_{c1}} + \overline{Z}_{s1} \; ; \; \overline{Z}_2 = \dfrac{\overline{Z}_{ch2}\overline{Z}_{c2}}{\overline{Z}_{ch2}+\overline{Z}_{c2}} + \overline{Z}_{s2} \\ \overline{Y}_s = \dfrac{1}{\dfrac{\overline{Z}_1\overline{Z}_2}{\overline{Z}_1+\overline{Z}_2}+\overline{Z}_{sm}} \; ; \; \overline{Y}_m = \dfrac{1}{\overline{Z}_m} \; ; \; \overline{Y}_r = \dfrac{1}{\overline{Z}_r + \dfrac{R_r}{g}} \end{cases} \tag{6}$$

At note 'B' in fig.2, the relation between $\overline{I}_m, \overline{I}_r$ and $\overline{I}_s$ can be written as:

$$\overline{I}_s = \overline{I}_r + \overline{I}_m \tag{7}$$

$$\begin{bmatrix} \overline{I}_m \\ \overline{I}_r \\ \overline{I}_s \end{bmatrix} = \overline{E} \begin{bmatrix} -\dfrac{1}{\overline{Z}_m} \\ \dfrac{1}{\overline{Z}_r} \\ \dfrac{1}{\overline{Z}_s} \end{bmatrix} \tag{8}$$

Hence, equation (7) can be written as:

$$\overline{E}(\overline{Y}_s + \overline{Y}_m + \overline{Y}_r) = 0 \tag{9}$$

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

$$\overline{Y}_s + \overline{Y}_m + \overline{Y}_r = 0 \tag{10}$$

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

$$\begin{cases} \mathrm{Re}(\overline{Y}_s + \overline{Y}_m + \overline{Y}_r) = 0 \\ \mathrm{Im}(\overline{Y}_s + \overline{Y}_m + \overline{Y}_r) = 0 \end{cases} \tag{11}$$

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, [7].

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 winding SEIG, [16-17].

III. RESULTS

A detailed study of steady-state performance of the dual stator winding 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 Eq. (1) are replaced by infinity.

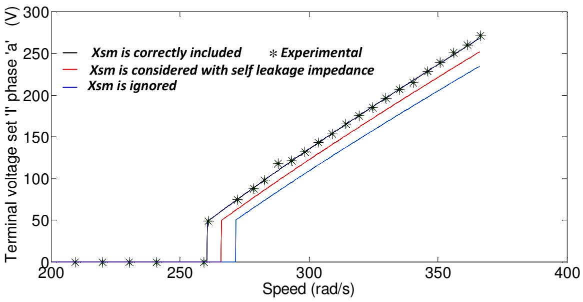

Fig. 3: Output stator voltage versus speed for different values of capacity.

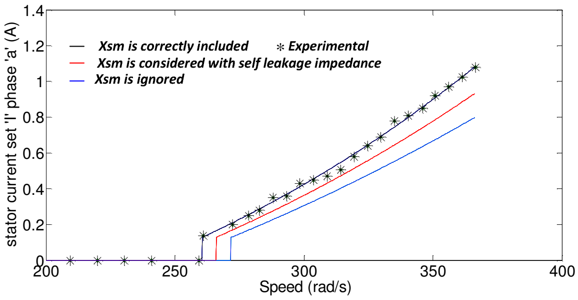

Fig. 4: Stator current versus speed for different values of capacity.

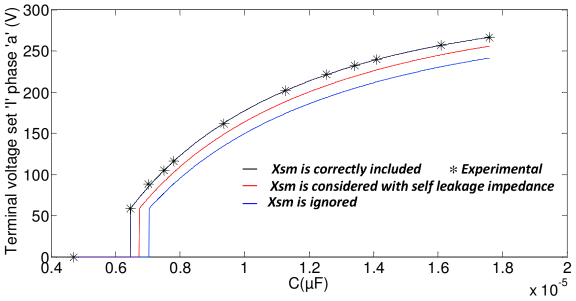

Fig. 5: Variation of terminal voltage with capacitance at no load

The influence of the stator mutual leakage impedance on the electrical performances is less significant. Indeed, if the mutual leakage impedance is neglected compared to the full model, the terminal voltage is about 9%. This variation is about 4.5% if the mutual leakage impedance is included as a self leakage impedance, fig 3 and 5.

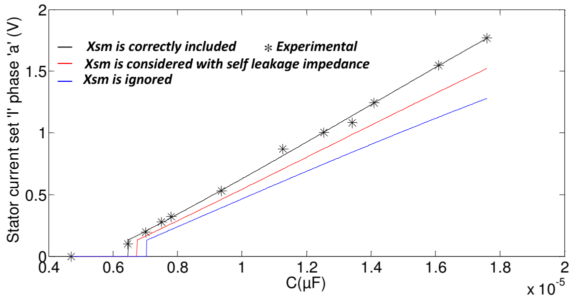

Fig. 6: Variation of stator current with capacitance at no load

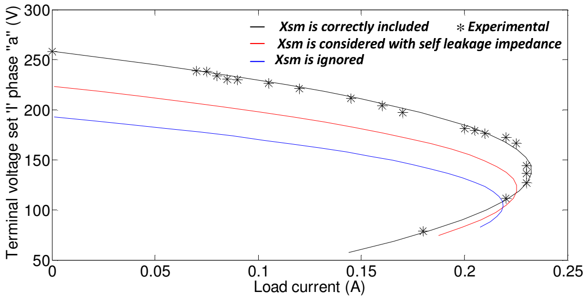

Fig. 7: Terminal voltage for stator 1 with load current

Stator current with speed and self capacitor presented in fig 4 and 6, compared to model 1, is about 2.23% for model 2 and it is around 4.5% for the model 3. In addition, a stator current increase is observed if the mutual leakage impedance is ignored. This allows us to note that performances obtained with model 2, if mutual leakage impedance is included as self impedance, are more acceptable in static mode operation. A comparative study between three models of including the self leakage impedance is observed. There by resulting in, an increase in current drawn by the machine. It is possible to note that, compared to model 3, model 2 is closest to model 1, witch one can notice the decrease of stator mutual impedance influence.

In nominal operation, the influence of the stator mutual leakage impedance on the electrical performances is less significant in static mode operation.

IV. DISCUSSION AND CONCLUSIONS

It is already mentioned in the introduction that in some works related to DSWIG, the stator mutual leakage impedance does not appear in their modelling process. To study the sensitivity of such factor, we have considered three possible cases where first the mutual leakage flux is suitably modelled, second it is considered as a self leakage flux and finally it is totally ignored. The investigation begins with a steady state analysis with experimental validation of DSWIG. The predictions made by model 1 are very close to the experience, it will serve further as a reference in evaluating results obtained with models 2 and 3. This is expected because in model 1, the mutual leakage impedance is correctly introduced. Those made by means of model 3 are the worst. After writing the adequate set of equations for a DSWIG, the mutual reactance is introduced exactly in the same way as for steady state operation.

If the mutual leakage impedance is not correctly modelled (model 2) or simply ignored (model 3), important differences in pics and magnitudes of simulated variables are observed, confirming the static analysis. In addition, all static characteristics in Figure 5 predicted by models 2 and 3 are very shifted relative to curves of the reference model. Consequently, model 2 and particularly model 3 are by no means recommended in control systems and drives.

Finally, in this paper, the sensitivity of the mutual leakage impedance on accuracy of DSIWG models is discussed. Three different models are used to investigate the impact of such parameter, in steady state analysis. It is proven that, if the mutual leakage impedance is not suitably introduced in the modelling process a significant loss of accuracy is resulting. Therefore, models considering that parameter as self impedance or particularly neglecting it are not recommended, especially in static operation.

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