Abstract—This paper studies and compares the use of double-cage and single-cage models for rotor speed stability determination of fixed-speed induction generators and analyzes the influence of grid parameters and reactive power compensation. The study proves that the double-cage model must be used for fixed-speed induction generator simulation as the single-cage model gives erroneous results. The influence of the dynamic reactive power compensator position on fixed-speed induction generator stability is also studied, it is shown that the use of a dynamic compensator device improves the speed stability of the fixed-speed induction generators.

Index Terms—Single-cage model, double-cage model, induction generator, speed stability.

I. INTRODUCTION

Squirrel-cage induction machines are known to have a high starting torque. It is surprising that the single-cage induction generator model, which predicts a low starting torque, is always used in the literature [1-7]. The use of an appropriate model of the fixed-speed induction generator is important for power system dynamic stability studies. The squirrel-cage induction generator is always modeled as a single-cage induction generator but, in the author’s opinion, a double-cage model must be used. During a network disturbance, if the speed increase is too high, the generator may not return to the prefault state. The determination of rotor speed stability [8] is critical for the generator disconnection from the grid. The protection philosophy of existing fixed-speed induction generators dictates disconnection of the unit at severe voltage sags. This principle may not be viable when the percentage of such generation units increases.

Using the data of an actual fixed-speed induction generator, the study shows that the critical speed in the double-cage induction generator model can be significantly higher than the value predicted by the single-cage model. In Section III, the influence of the low voltage transformer impedance and wind park transformer impedance on induction generator speed stability is studied. The torque-speed curve shows that, for low impedances, the speed stability predicted by the double-cage model is always greater than that predicted by the single-cage model. Section V discusses the influence of reactive power devices on the speed stability. The results show that they have a significant improvement when the double-cage model is used.

II. SQUIRREL-CAGE INDUCTION GENERATOR MODELS

In the literature [1-7], induction generators are usually modeled using the single-cage model of Fig. 1a. This model is suitable for wound rotor induction generators. Nevertheless, it is not adequate for the squirrel-cage induction generator when the slip varies widely.

Squirrel-cage induction generators must be modeled using a double-cage model. Figs. 1b and 1c show two different double-cage models used in the literature. For example, the model in Fig. 1b is for the double-cage induction machine used in EMTP-RV [9] and the one in Fig. 1c is used in PSCAD-EMTDC [10]. In [11], it is shown that different equivalent circuits can be equal to each other. The conversion of parameters between the double-cage models of Fig. 1 is discussed in [12]. An algorithm to calculate induction
parameters can be calculated from Table 2 as

\[ R' = r_0 Z_s; \quad R'_1 = r_z Z_b; \quad R'_2 = r_e Z_b; \quad X'_{sd} = x_{sd} Z_s; \quad X'_{sd} = x_{sd} Z_b; \quad X'_{2sd} = x_{2sd} Z_s, \]

where the impedance base is

\[ U = 690 \text{ V}, \quad f = 50 \text{ Hz}. \]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>INDUCTION GENERATOR MANUFACTURER DATA (U = 690 V, f = 50 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKW</td>
<td>PFK</td>
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<tr>
<td>1300</td>
<td>0.90</td>
</tr>
</tbody>
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<tr>
<th>Table 2</th>
<th>SINGLE-CAGE AND DOUBLE-CAGE PER-UNIT PARAMETERS (U = 690 V)</th>
</tr>
</thead>
</table>

Single-cage model

| \( r_s \) | 0.0056 |
| \( x_{sd} \) | 0.0811 |
| \( x_{m} \) | 3.1759 |

Double-cage model Fig. 1b

| \( r_s \) | 0.0066 |
| \( x_{sd} \) | 0.0490 |
| \( x_{m} \) | 1.0490 |

Double-cage model Fig. 1c

| \( r_s \) | 0.0066 |
| \( x_{sd} \) | 0.1448 |

generator parameters from manufacturer data by using the equivalent circuit of Fig. 1b is developed in [13].

Table 1 presents the induction manufacturer data of a 1300 kW induction generator. Table 2 shows the double-cage parameters of Fig. 1b obtained from the manufacturer data of Table 1. The double-cage parameters of Fig. 1b were calculated using the algorithm of [13]. Table 2 also shows the double-cage parameters of Fig. 1c. The conversion of parameters from Fig. 1b to Fig. 1c was made with the equations in [12]. The single-cage parameters of Table 2 were calculated using the information about full load slip and maximum torque. The single-cage parameter determination is detailed in [14]. The real values of the induction generator parameters can be calculated from Table 2 as

\[ Z_s = U^2/P, \]

where \( U \) being the rated line voltage and \( P \) the rated power.

Electromagnetic transient programs like PSCAD-EMTDC or EMTP-RV have equivalent circuit parameters or manufacturer data as an option of data entries. It is important to note that the manufacturer data option does not work correctly in these programs. Fig. 3 plots the torque-speed curves calculated by PSCAD-EMTDC and EMTP-RV represented by a broken line and a dotted line, respectively. The correct torque-speed curve is represented by a solid line. This problem is discussed in detail in [12]. The main reason for this inaccuracy is that the algorithms used by these programs to calculate the induction generator parameters ignore the maximum torque.

### III. INFLUENCE OF THE NETWORK IMPEDANCE

The wind farm was modeled with the circuit of Fig. 4, where the induction generators are modeled with one equivalent induction generator. Low voltage transformers are represented by the impedance \( x_{gen} \), the wind farm substation transformer is represented by the impedance \( x_{sub} \) and the system impedance is represented by the impedance \( x_{net} \). The addition of these external impedances is labeled as \( x_c \).

![Fig. 4. Phase to neutral equivalent circuit](image)
Figs. 5 and 6 show the influence of the external impedance \( x_e \) on the torque-speed and the current-speed curves of the double-cage and single-cage induction generator models. The normalized torque \( T(s)/T_n \) and the normalized current \( I(s)/I_n \), where \( T_n \) is the nominal torque and \( I_n \) the nominal current, can also be seen.

Figs. 5 and 6 were calculated considering the voltage at the induction generator equal to 1. Then, when the induction generator is at its nominal power, the voltage in the network depends on the external impedance according to the relation

\[
|Z_{\text{net}}| = \frac{|Z_g + jx_e|}{|Z_e|}
\]

(3)

where the impedance \( Z_g \) is the induction generator impedance at nominal slip.

Figs. 5 and 6 show that the external impedance has a significant influence on the induction generator stability. Fig. 5a reveals that when the mechanical torque provided by the wind turbine has their rated value, \( T = -1 \), the double-cage model with the parameters of Table 2 has a critical speed greater than 1.5 p.u. for an external impedance of \( x_e = 0.1 \) or lower. When the external impedance is \( x_e = 0.15 \) the critical speed is 1.1825, and for \( x_e = 0.2 \) it is 1.1036. The single-cage model in Fig. 6 shows the critical speeds 1.3997, 1.2395, 1.1611, 1.1167 and 1.0892 for an external impedance \( x_e \) of 0, 0.05, 0.1, 0.15 and 0.2.

Fig. 5 shows that the decrease of the external impedance \( x_e \) has a greatly improves the speed stability of the induction generator. Since the network impedance \( x_{\text{net}} \) cannot be changed easily, the decrease of the low voltage transformer impedance \( x_{\text{gen}} \) or the substation transformer impedance \( x_{\text{sub}} \) can be a good solution to improve the speed stability of the induction generator.

IV. INDUCTION GENERATOR STABILITY

In this section the dynamic behavior of the induction generator in the presence of voltage sags is studied. The dynamic equations that correspond to the equivalent circuits of Figs. 1a, 1b and 1c are detailed in [12].

Figs. 7 and 8 show the effects of a voltage sag with the voltage profile of the Nordel grid code [15] on the induction generator speed and rms voltage. In Fig. 7 the double-cage model is used with the data of Table 2 whereas in Fig. 8 the single-cage model is used. The inertia constant [12] is \( H = 2.23 \text{ s} \). The rms voltage profile applied to the circuit of Fig. 4 is indicated by a broken line. When the external impedance is \( x_e = 0.1 \), the rms voltage value before the voltage sag is \( u_{\text{net}} = 1.0533 \), which corresponds to an induction generator voltage, \( u_e = 1.0 \), when the generator works at the nominal power. It is assumed that the mechanical torque provided by the wind turbine rotor to the induction generator is constant during the fault and that its value is its rated value.

Fig. 7 shows that the induction generator double-cage model is stable whereas the single-cage model in Fig. 8 predicts that the induction generator is unstable. This is because the torque-
speed curve in the single-cage model decays very fast when the speed is greater than the speed of the maximum torque. This effect can be clearly observed in Fig. 2.

Figs. 9 and 10 show the effects of a voltage sag with the voltage profile of the Spanish grid code [18] on the induction generator speed and rms voltage. In Fig. 9 the double-cage model is used with the data of Table 2 whereas in Fig. 10 the single-cage model is used.

Fig. 9 shows that the induction generator double-cage model is stable with an external impedance $x_e = 0.05$. The single-cage model is stable with the ride through profile from the Spanish grid code in the case without external impedance, $x_e = 0$, but it is very close to instability because with an external impedance of $x_e = 0.005$ it is unstable, as can be seen in Fig. 10.

V. INFLUENCE OF A DYNAMIC REACTIVE COMPENSATION

Static stability studies give a global understanding of the influence of dynamic reactive power devices on the torque-speed curve. Several studies [15-17] prove that the use of dynamic power reactive devices improves fixed-speed induction generator stability. In this work, the capacitive impedance of the dynamic reactive compensator is varied so that the voltage at given terminals is the nominal voltage. When this voltage cannot be reached, the dynamic reactive compensator is modeled with a constant capacitive admittance. The admittance in p.u. of the reactive power compensator is labeled as $y_c$.

Fig. 4 shows the three different positions where the dynamic
reactive power compensation device can be connected: point 1, at the low voltage induction generator transformer side, point 2, at the low voltage substation transformer, and point 3 at the high voltage substation transformer. Fig. 11 shows the torque-speed curve for a capacitor of value \( y_c = 1 \) and an external impedance \( x_{ext} = 0.20 \) composed of \( x_{gen} = 0.05 \), \( x_{sub} = 0.10 \) and \( x_{net} = 0.05 \). The critical speeds predicted by the double-cage model are 1.1645, 1.1609, 1.1248 and 1.1037 for the cases of positions 1 to 3 and without the capacitor. For the single-cage model, the critical speeds are 1.1140, 1.1128, 1.1424, 1.1817 and 1.2459 for the torques –1, –0.8 and –0.6. The single-cage model predicts a critical speed of 1.1038 p.u. When the reactive power device is connected at different places, all the critical speeds are greater than 1.5 p.u. The critical speeds calculated when the single-cage model is used are 1.1424, 1.1384, 1.1295, and 1.1167 for the cases of positions 1 to 3 and without the capacitor.

Fig. 12 shows the influence of the capacitor position on the torque-speed curve for a capacitor of value \( y_c = 2 \) and an external impedance \( x_{ext} = 0.20 \) composed by \( x_{gen} = 0.05 \), \( x_{sub} = 0.10 \) and \( x_{net} = 0.05 \). The double-cage model in Fig. 13 predicts a critical speed in the case without capacitor of 1.1038 p.u. When the reactive power device is connected at a low voltage level and the worst improvement occurs at the transmission level.

Fig. 14 compares the torque-speed curves of the double-cage and single-cage models of Figs. 11, 12 and 13. All the torque-speed curves correspond to the case when the capacitor is in position 1. Fig. 14 also shows the influence of the load point on the critical speed. The torque of three load points of torque –1, –0.8 and –0.6 is represented by broken lines. In Fig. 14a, the double-cage model always has a critical speed greater than 1.5 p.u. The single-cage model predicts a critical speed of 1.1424, 1.1817 and 1.2459 for the torques –1, –0.8 and –0.6. In Fig. 14b the double-cage model has a critical speed of 1.1645 for the torque of –1 p.u. and the critical speed is greater than 1.5 p.u. for the torques –0.8 and –0.6. The single-cage
The influence of the connection point has been studied. The reactive power compensators also improves speed stability. Consequently, the model predicts better speed stability than the single-cage model. The influence of external impedance on the induction generator stability is demonstrated. Consequently, the double-cage model predicts better speed stability than the single-cage model has a critical speed of 1.1446, 1.1825 and 1.2452 for the torques –1, -0.8 and –0.6. In Fig. 14c the double-cage model has a critical speed of 1.4869 p.u. for the torque –1. The single-cage model has a critical speed of 1.1446, 1.1825 and 1.2452 for the torques –1, -0.8 and –0.6.

VI. CONCLUSIONS

The effects of voltage sags on the speed stability of the induction generator when single- and double-cage models are used have been investigated. The study reveals that the double-cage model predicts better speed stability than the single-cage model. The influence of external impedance on the induction generator stability is demonstrated. Consequently, the reduction of the substation transformer impedance greatly improves induction generator stability.

In addition, the study proves that the use of dynamic reactive power compensators also improves speed stability. The influence of the connection point has been studied. The best improvement is obtained when the device is connected at a low voltage level and the worst improvement occurs at the transmission level.

VII. ACKNOWLEDGMENTS

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REFERENCES