ANALYSIS OF PARALLEL-OPRATED SINGLE-PHASE SELF-EXCITED INDUCTION GENERATORS

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ABSTRACT

In this paper, a new methodology is presented to analyse the parallel operation of single-phase self-excited induction generators (SEIGs) in a distribution system. The model is then employed by analyzing starting currents and short circuit currents contributions from the SEIGs. Relevant simulation and analysis are performed using Matlab/Simulink. It is found that the aggregation model proposed in this paper can give satisfactory results.

INTRODUCTION

Distributed Generation (DG) promises many potential benefits, including peak shaving, price hedging, fuel switching, improved power quality and reliability, increased efficiency, and improved environmental performance. DG will account for a significant part of new generation capacity and small-scale distributed generation, ranging from a few kW to 10MW, will play a part in this. Compared with the synchronous machine and DC machine with same capacities and similar conditions, parallel operated induction generators hold the following advantages: robustness, reduced size, decreased cost, no synchronisation operations required and high reliability [2]. In rural autonomous areas, the self-excited single-phase squirrel cage induction machines, driven by small wind turbine or mini-hydro turbines, are being used as the generator for the purpose of supplying smaller loads of less than 5 kW [3]. Such a group of induction machines can contribute to dynamic performance of the distribution system, for instance in fault current, hence, it is important to properly represent the group of induction machines in simulation so that the accurate dynamic responses can be predicted. The main disadvantage of a detailed model is the computational burden involved in the simulation results. In order to avoid the necessity of developing a detailed distributed network model of wind farms with tens or hundreds of wind turbines and their interconnections, an aggregated model is required. In most previous research work, the parameters of the aggregate induction machine model, which is used to predict starting currents or fault currents, were obtained from the voltage equations and mechanical equation [4]. Using matrix equation, another effect, which was considered in the transient performance of a system of SEIGs operating in parallel, is proposed by [6]. Moreover, the aggregation models have been employed to study the steady state of the distributed system based on the transformer-type variation of the equivalent circuit [7] or singular perturbation theory [8].

This paper addresses a method of investigating the operation of multiple SEIGs connected to a common bus and same phase. Section II describes the aggregation method for SEIGs. The comparison of starting currents and fault currents between results obtained using the aggregation model and those from the summation of response from each SEIG are performed in Section III. Matlab/Simulink is used in all simulations.

AGGREGATED MODEL OF SEIGs

Figure 1 shows an equivalent circuit described by [3] for the aggregated model of parallel-operated SEIGs connected to the same bus and same phase. In this system, all machines are operated at a common terminal voltage and a common frequency.

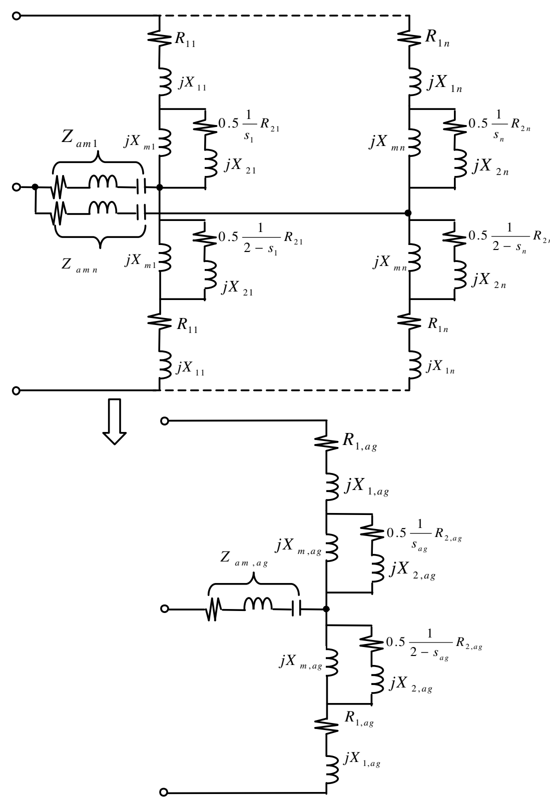

Figure1*. An equivalent circuit of the proposed aggregated Model for SEIGs*

A. Main winding parameters

The aggregated main winding parameters of single-phase self-excited induction machines can be obtained from no-load and locked-rotor tests that are similar to these applied to 3-phase induction machines [4]. With the exception of the capacitor-run machines, these tests are made with the auxiliary winding kept open.

When performing the no-load test, the slips of all the induction machines in a group are approaching zero. As a result, the no load impedance of machine index i, Z_i ,is:

$$Z_i = (2R_{1i} + 0.25R_{2i}) + j\omega(2l_{1i} + l_{2i} + l_{mi}) \quad (1)$$
$$i = 1, 2, \cdots n$$

where

n : number of induction machine in group
R_1: main winding stator resistance
l_1 : main winding stator leakage inductance
R_2 : rotor resistance referred to stator
l_2 : rotor leakage inductance referred to stator
l_m : magnetizing inductance

Consequently, the aggregated no-load impedance, $Z_{NL,ag}$, is given by

$$Z_{NL,ag} = 1/(\sum_{i=1}^{n} \frac{1}{Z_i}) \quad (2)$$

Simple analysis of the equivalent circuit shows that:

$$Z_{NL,ag} = (2R_{1,ag} + 0.25R_{2,ag}) + j\omega(2l_{1,ag} + l_{2,ag} + l_{m,ag}) \quad (3)$$

Subscript ag refers to aggregated equivalent value, e.g., $R_{1,ag}$ represents main winding stator resistance of aggregated model.

The following considers all machines in the group starting at the same time. This may occur, for example, following a system disturbs. At machine starting, the slip of all induction generators in the group is approaching 1. As a result, the locked-rotor impedance of machine index i, Z_{Li} , is:

$$Z_{Li} = (2R_{1i} + R_{2i}) + j2\omega(l_{1i} + l_{2i}) \quad (4)$$
$$i = 1, 2, \cdots n$$

Consequently, the aggregated locked-rotor impedance, $Z_{LR,ag}$, is given by

$$Z_{LR,ag} = 1/(\sum_{i=1}^{n} \frac{1}{Z_{Li}}) \quad (5)$$

Simple analysis of the equivalent circuit shows that:

$$Z_{LR,ag} = (2R_{1,ag} + R_{2,ag}) + j2(\omega l_{1,ag} + \omega L_{2,ag})$$

To calculate the values of $l_{1,ag}$ and $l_{2,ag}$, the ratio between l_1 and l_2 can be obtained from an IEEE standard [1]. This means that the group of machines may be divided into subgroups to enable more accurate parameters because different machine classes may have different ratios.

The aggregated nominal power (S_{ag}) and the moment of inertia (J_{ag}) that is a function of rotor mass and geometry can be obtained from [5]:

$$S_{ag} = \sum \alpha_i S_i \quad (6)$$
$$i = 1, 2, \cdots n$$

where

$$\alpha_i = P_i / P_{ag} \quad (7)$$

$$P_{ag} = \sum_{i=1}^{N} P_i \quad (8)$$

$$H_{ag} = (\sum_{i=1}^{N} H_i P_i) / \sum_{i=1}^{N} P_i \quad (9)$$

$$J_{ag} = 2H_{ag} P_{ag} / \omega_s^2 \quad (10)$$

where

P_{ag} : rated power of the aggregated model
P_i: rated power of each machine in group
S_i: nominal power of each machine in group
H_i : inertia power of each machine in a group
ω_s : synchronous angular speed
H_{ag} : inertia constant of the aggregated model

B. Auxiliary winding parameter

The definition of aggregated auxiliary winding parameters of SEIGs has not received any attention. Consequently, a new formulation has been developed. The aggregated auxiliary winding parameters of single-phase self-excited induction machines can be obtained from voltage and current equations. The basic principle is that the current of detailed model taken from distributed network is equal to that of aggregated model.

$$\begin{bmatrix} V_m \\ V_a \end{bmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{bmatrix} I_m \\ I_a \end{bmatrix} \quad (11)$$

where

$$Z_{11} = Z_1 + Z_f + Z_b$$
$$Z_{12} = -Z_{21} = -ja(Z_f - Z_b)$$
$$Z_{22} = -j\frac{1}{\omega C} + R_a + j\omega l_a + a^2(Z_f + Z_b)$$
$$Z_1 = R_1 + j\omega l_1$$
$$Z_f = (j0.5\omega l_m(\frac{R_2}{s} + j\omega l_2)) / (\frac{R_2}{s} + j(\omega l_m + \omega l_2))$$
$$Z_b = (j0.5\omega l_m(\frac{R_2}{2-s} + j\omega l_2)) / (\frac{R_2}{2-s} + j(\omega l_m + \omega l_2))$$

V_m and I_m : main winding voltage and current
V_a and I_a : auxiliary winding voltage and current
Z_f and Z_b : forward and backward reactance
R_a : auxiliary winding stator resistance
l_a : auxiliary winding stator leakage inductance
C : capacitor for staring

When n numbers of single-phase self-excited induction machines were operated in parallel, the equation 11 can be written with ag that represents aggregated values as:

$$\begin{bmatrix} V_m \\ V_a \end{bmatrix} = \begin{pmatrix} Z_{11,ag} & Z_{12,ag} \\ Z_{21,ag} & Z_{22,ag} \end{pmatrix} \begin{bmatrix} I_{m,ag} \\ I_{a,ag} \end{bmatrix} \quad (12)$$

$$I_{m,ag} + I_{a,ag} = \sum_{i=1}^{n} I_{mn} + \sum_{i=1}^{n} I_{an} \quad (13)$$

where

$V_m = V_a$

$Z_{11,ag}, Z_{12,ag}$ and $Z_{21,ag}$ have same calculated methods as $Z_{11}, Z_{12,}$ and Z_{21}.

$\sum_{i=1}^{n} I_{mn} + \sum_{i=1}^{n} I_{an}$ can be calculated from detailed modelling.

because of

$$Z_{22,ag} = -j\frac{1}{\omega C_{ag}} + R_{a,ag} + j\omega l_{a,a} + a^2(Z_{f,ag} + Z_{b,ag}) \quad (14)$$

Rearranging gives:

$$R_{a,ag} + j\omega l_{a,a} = Z_{22,ag} + j\frac{1}{\omega C_{ag}} - a^2(Z_{f,ag} + Z_{b,ag}) = Z'_{22,ag}$$

hence

$R_{a,ag}$: real part of $Z'_{22,ag}$

$\omega l_{a,ag}$: imaginary part of $Z'_{22,ag}$

The constant speed aggregated wind turbine model has been discussed in the literature [5] and there is no repeat in this paper.

CASE STUDY

The following simulations were performed using Matlab/Simulink for obtaining the starting current and the fault currents contributions from a group of SEIGs. The system, consisting of four induction generators connected to the same bus and same phase, as shown in Fig 2, is employed in the case studied. The parameters of the SEIGs are shown in appendix. When the rotor speed of a SEIG is over 75% of synchronous speed, the auxiliary winding is disconnected. That means the group of machines may be divided into subgroups to enable gathering of accurate parameters when starting currents are investigated.

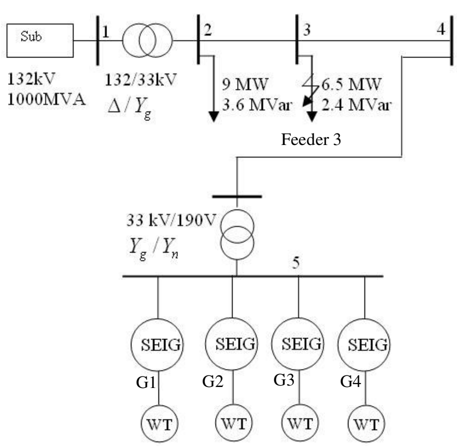

Figure2. *Case study network*

From Figure 1, the aggregation model is used to combine all four SEIGs into a single unit. This is calculated by applying equations (2) to (14) and the parameters for the aggregation model are shown in the appendix. The column G_{ag1} in the table describes the parameters of the aggregated model where no sub-group for SEIGs has been used and the parameter of G_{ag2} is calculated by dividing SEIGs into two group according to their different slips. The starting currents and three-phase fault currents will be studied in these cases. For the fault simulation, a three-phase short circuit fault located at feeder 3 at 2s is applied and the fault tripped out at 2.3s. Comparison of the responses between using the detailed model and the aggregated model is concerned in figure 3,4,5,and 6.

Fig.3 and Fig.4 show the three-phase current waveforms at bus 5 of the detailed model and aggregated model for generator starting. It can be seen that the current waveforms of the aggregate model can be accepted when the SEIGs were divided into sub-group according to their different slip. Fig.5 and Fig.6 shows the responses of the three-phase fault currents of the detailed model and aggregated models. The fault current waveforms of the aggregated models both agree closely with those of the detailed model. Simulation time in a desktop PC can be saved 37.5% and 25% for G_{ag1} and G_{ag2} model respectively comparing the used time of detailed model.

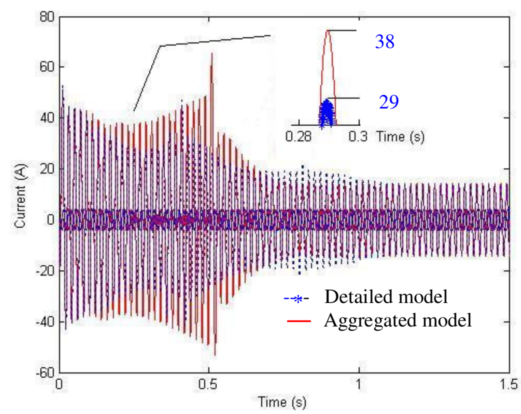

Figure3. *Generator starting currents for G_{ag1} model and detailed model*

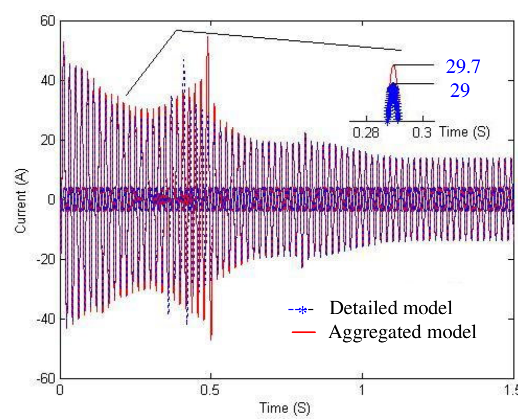

Figure4. *Generator starting currents for G_{ag2} model and detailed model*

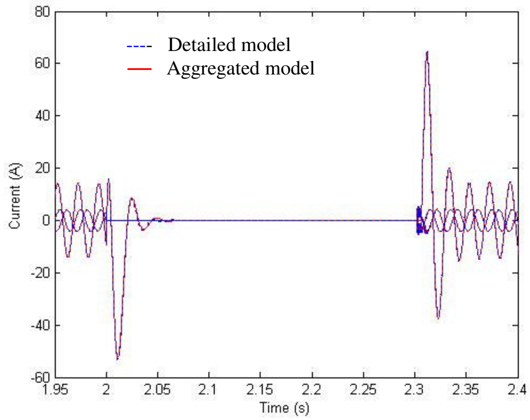

Figure5. *Three-phase short circuit fault currents for* G_{ag1} *model and detailed model*

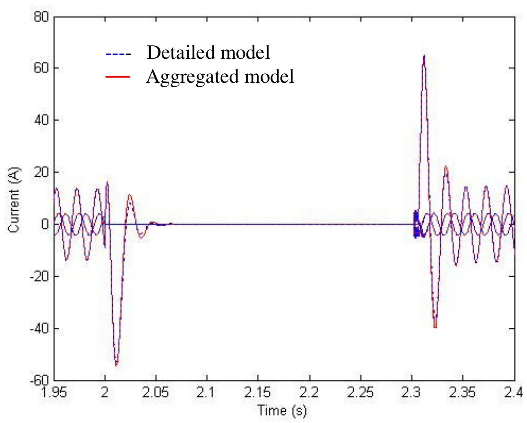

Figure6. *Three-phase short circuit fault currents for* G_{ag2} *model and detailed model*

CONCLUSION

A new methodology for the development of aggregated SEIGs model was been realized in this paper. The research results show that the proposed methodologies will reduce the complexity of an examined distributed system and accelerate the simulation time in various applications. The important point is that the responses of both systems will provide a good match. From the simulations, it is clear that the behavior of SEIGs with different slips can be better predicted using an aggregated model with sub-groups for simulating generator starting. On the other hand, there appears no same requirement to use subgroups for the fault studied. The research work continues to the cases where a generator group is composed of more SEIGs, the SEIGs connect the different phases and are dispersed in network.

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APPENDIX

Table 1. Detail for rate values and parameters of the SEIGS and aggregated model

	G_1	G_2	G_3	G_4	$G_{ag,1}$	$G_{ag,2}$	
Power (VA)	746	500	1000	1350	3596	2246	1350
$R_1(\Omega)$	2.2	2.89	2.02	2.8	0.64	0.84	2.8
$X_1(\Omega)$	3.05	3.28	2.32	6.41	0.83	0.94	6.41
$R_2(\Omega)$	4.5	4.02	4.12	3.97	1.12	1.3	3.97
$X_2(\Omega)$	3.05	3.28	2.32	6.41	0.83	0.94	6.41
$X_m(\Omega)$	73	47	55.5	80	15.4	19	80
$R_a(\Omega)$	7.8	7.7	7.14	5.2	2.03	2.62	5.2
$X_a(\Omega)$	3.52	4.3	2.68	11.78	1.3	1.2	11.78
J ($kg.m^2$)	0.0146	0.0146	0.0146	0.0146	0.0584	0.0438	0.0146
N	1.18	1.18	1.18	1.18	1.18	1.18	1.18
C (μF)	348	289	358	226	1221	995	226
Slip (%)	1	1	1	0.67	0.95	1	0.67