Considerations regarding the Control of a Mixed Genset based on the usage of Synchronous and Asynchronous Generator

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Abstract: This paper proposed a voltage and frequency control algorithm of a mixed group based on the usage of synchronous and asynchronous generator. The control algorithm involves the presence of three control loops that implement for the synchronous generator - the excitation and torque control, and for the asynchronous generator – the torque control. In the paper is used the orthogonal model for the both two generators. The usage of wind energy and of the water accumulations with variable flow imposed the asynchronous generator beside the synchronous one in nowadays energy power systems. There are conducted simulation studies regarding the gensets (synchronous and asynchronous generator) behavior under several load variations. The conclusions prove and validate the solution of using of mixed gensets within the electric energy power networks.

Key-Words: - synchronous generator, asynchronous generator, orthogonal model, modeling and simulation, control algorithms, mixed genset.

1 Introduction

The fact that the synchronous generators deliver active and reactive power independently imposes their usage in classical energy systems. In last period through the attraction of renewable resources, such as: wind energy, the asynchronous generator due to the fact that it operates at variable speed is more and more used and there result energy systems with asynchronous and synchronous generators as considered in the present paper. The system configuration offers an increased stability of the energy system through the asynchronous generator functioning as an amortize at sudden load variations.

In the present paper there is used the orthogonal model for the both two generators, their parameters being determined through a method developed by the authors [1][6].

2 Mixed power energy systems modeling

In figure 1 there is depicted the structure of a mixed power energy system equipped with both synchronous and asynchronous generator.

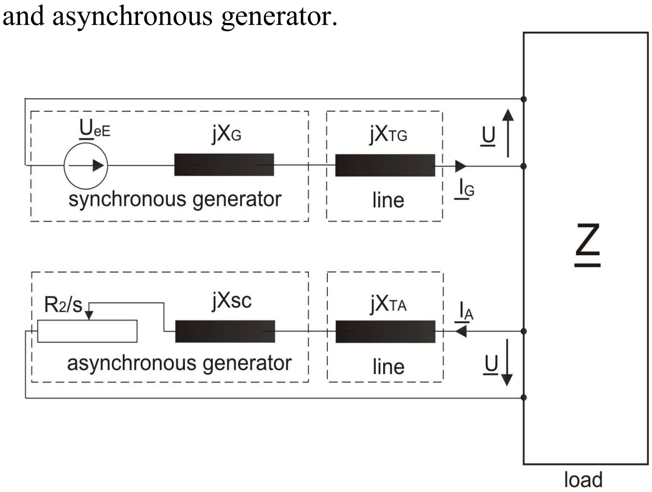


Figure 1. Mixed power energy system with synchronous and asynchronous generator.

The both generator are delivering the power on a load $\underline{Z}$ with variable value.

The following notations are used in Figure 1:

jX_G – the synchronous reactance of the synchronous generator.

jX_{TG} – the transport line's reactance between the synchronous generator and the load.

R2/s – the equivalent resistance of the inducer and air gap at the asynchronous generator.

jXsc – short-circuit reactance of the asynchronous generator.

jX_{TA} - the transport line's reactance between the asynchronous generator and the load.

The functioning in dynamic regime of the systems in the case of generators equipped with voltage and frequency controllers is described by the following system of differential equations.

A) Synchronous generator (SG) equations. [1][2][6]

The synchronous generator orthogonal model is defined by the equations:

$$U\sqrt{3}\sin\theta = -R_d I_d - L_d \frac{dI_d}{dt} + \omega L_q I_q + M_E \frac{dI_E}{dt} + \\ + M_D \frac{dI_D}{dt} - \omega M_q I_q \quad (1)$$

$$U\sqrt{3}\cos\theta = -\omega L_d I_d - R_q I_q - L_q \frac{dI_q}{dt} - \\ + \omega M_E I_E + \omega M_D I_D + M_Q \frac{dI_Q}{dt} \quad (2)$$

$$U_E = -M_E \frac{dI_d}{dt} + R_E I_E + L_E \frac{dI_E}{dt} + M_{ED} \frac{dI_D}{dt} \quad (3)$$

$$0 = -M_D \frac{dI_d}{dt} + M_{ED} \frac{dI_E}{dt} + R_D I_D + L_D \frac{dI_D}{dt} \quad (4)$$

$$0 = -MQ \frac{dI_q}{dt} + R_Q I_Q + L_Q \frac{dI_Q}{dt} \quad (5)$$

$$J\frac{d\omega}{dt} = p_1[(L_d - L_{q)} I_d I_q + M_E I_q I_E - M_Q I_d I_Q + \\ + M_D I_q I_D] - M_{REZ} \quad (6)$$

where:

Rd - stator resistance

R_D – the amortization's winding resistance from d-axis

R_Q - the amortization's winding resistance from q-axis

R_E – the excitation's winding resistance

L_d - the stator self-inductance from d-axis

L_q- the stator self-inductance from q-axis

L_E - the self-inductance of the excitation winding

L_D – the self-inductance of the amortization winding from d-axis

L_Q - the self-inductance of the amortization winding from q-axis

M_E – mutual inductance between the stator and excitation windings

M_D – the mutual inductance between stator winding and the d-axis amortization winding

M_Q – the mutual inductance between stator winding and the q-axis amortization winding

M_{ED}- the mutual inductance between the excitation winding and the d-axis amortization winding

J – inertial moment

Id, Iq – stator currents

I_E- excitation current

I_D,I_Q – amortization currents

ω =2*pi*f – angular velocity

M_{REZ} – motor torque at synchronous generator

B) Asynchronous generator (AG) equations.[1][3][7]

The asynchronous generator orthogonal model is defined by the equations:

$$U_d = R_1 I_d + L_1 \frac{dI_d}{dt} - \omega_1 L_1 I_q + M\frac{dI_{dr}}{dt} - \omega_1 M I_{qr} \quad (7)$$

$$U_q = \omega_1 L_1 I_d + R_1 I_q + L_1 \frac{dI_q}{dt} + \omega_1 M I_{dr} + M\frac{dI_{qr}}{dt} \quad (8)$$

$$0 = M\frac{dI_d}{dt} - M(\omega_1 - \omega) I_q + R_2 I_{dr} + L_2 \frac{dI_{dr}}{dt} - \\ - L_2(\omega_1 - \omega) I_{qr} \quad (9)$$

$$0 = M(\omega_1 - \omega) I_d + M\frac{dI_q}{dt} + L_2(\omega_1 - \omega) I_{dr} + \\ + R_2 I_{qr} + L_2 \frac{dI_{qr}}{dt} - \quad (10)$$

$$M_{REZ} = p_1 M (I_q I_{dr} - I_d I_{qr}) \quad (11)$$

where:

R_1- the stator resistance

R_2- the rotor resistance

L_1- stator self inductance

L_2- rotor self inductance

M – the mutual inductance between the stator and rotor windings

Id,Iq – stator currents

Idr,I qr – rotor currents

ω_1 =2pi*f_1 – the stator angular velocity

ω = 2pi*f_1 – the rotor angular velocity

M_{REZ} – motor torque at asynchronous generator

In the Figure 2 is presented the control structure on which the proposed control algorithm was designed and implemented. There are considered three controllers for:

- Synchronous generator excitation control;
- Synchronous generator turbine torque control;
- Asynchronous generator turbine torque control.

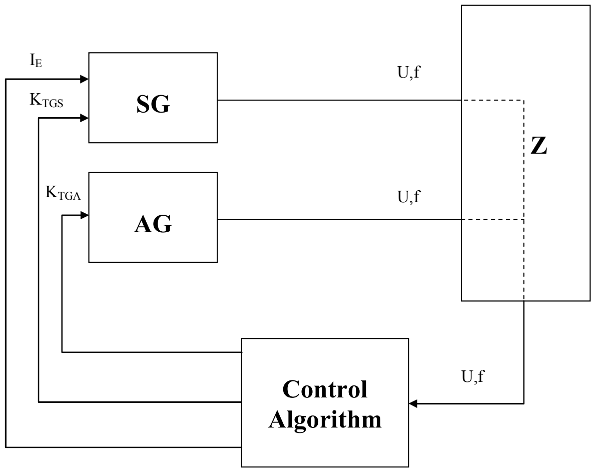


Figure 2. The control system.

By varying the value of the R load resistance, the system is loaded until its dynamic stability limit.
The load is proportional with the power, fact that imposes the following condition:

$$\frac{K_{TGS}(\omega_{0GS}-\omega)\omega}{p_{IGS}^2 P_{NGS}} = \frac{K_{TGA}(\omega_{0GA}-\omega(1-s))\omega(1-s)}{p_{IGA}^2 P_{NGA}} \quad (12)$$

where:
K_{TGS} – is the torque constant of the turbine at the synchronous generator
ω_{0GS} – is the angular velocity for without load functioning regime of the turbine at synchronous generator
p_{IGS}- is the number of synchronous generator 's pole pairs
P_{NGS}- is the synchronous generator's nominal power
K_{TGA} – is the torque constant of the turbine at the asynchronous generator
ω_{0GA} – is the angular velocity for without load functioning regime of the turbine at asynchronous generator
p_{IGA}- is the number of asynchronous generator 's pole pairs
P_{NGA}- is the asynchronous generator's nominal power.

The initial and final values of mixed genset functioning regime are obtained by solving the equation system:

$$U_d = 0.2\omega x \quad (13)$$

$$U_q = -0.2\omega z + 0.98wy \quad (14)$$

$$0 = w(628-\omega) - 0.98xy \quad (15)$$

$$U_d = -0.6\omega a - 0.5\omega c \quad (16)$$

$$U_q = 0.6\omega g + 0.5\omega d \quad (17)$$

$$0 = -0.5s\omega a + 0.65b - 0.7s\omega c \quad (18)$$

$$0 = 0.5s\omega g + 0.7s\omega b + 0.65c \quad (19)$$

$$0 = v(628 - \omega + \omega s) + 0.5ab - 0.5gc \quad (20)$$

$$U_d = R(z-g) - T(x-a)\omega \quad (21)$$

$$U_q = \omega T(z-g) + R(x-a) \quad (22)$$

$$6000 = \sqrt{U_d^2 + U_q^2} \quad (23)$$

$$\omega = 314 \quad (24)$$

$$w(628-\omega) = v[628 - \omega(1-s)](1-s) \quad (25)$$

where are introduced the following notations:

$i_q = a$ q-axis stator current for AG
$i_d = g$ d-axis stator current for AG
$i_{qr} = c$ q-axis rotor current for AG
$i_{dr} = b$ d-axis rotor current for AG
$I_q = x$ q-axis stator current for SG
$I_d = z$ d-axis stator current for SG
$I_E = y$ excitation current for SG
$I_D = h$ d-axis amortization current for SG
$I_Q = f$ q-axis amortization current for SG
$\underline{Z_1} = R + jX$ load impedance
K_{TGS} torque coefficient for SG
K_{TGA} torque coefficient for AG
$U_E = m$ excitation voltage for SG

The electrical load connected at the both two generators is defined by the relation: $\underline{Z} = R + j\omega T$
For any time moment, for $U = \sqrt{U_d^2 + U_q^2}$ and $\omega = 2\pi f$ known via direct measurements performed in the power network, solving the system equation (13)...(25) there can be computed the values of the state variables.

3 The control algorithm

The independent acting of the three controllers (excitation, AG torque, SG torque) would lead to an unequal distribution of the two generators. As a result, one generator will be overloaded, and the other one will be discharged, the issue could lead to the destruction of the overloaded generator. The goal of the application is to realize the coupling of the three loops by using the presented algorithm in order to load proportionally with

the nominal power the both two generators. By modifying the electric load of the system, the voltage and frequency won't be anymore the nominal one (they rise or fall in accordance to the load).
The separate functioning of the controllers increases the unbalance in the system's functioning in the term that the synchronous generator's excitation controller will sense the voltage drop. Also both the excitation current and the synchronous generator's torque at the turbine will be increased and, as a consequence, the synchronous generator will overload and the asynchronous generator will discharge.
Through the proposed algorithm there are restored the three variables at nominal values.
The considered control algorithm is implemented by parsing the following steps:
1) There are determined for an reference (set-point) regime (ex: the without load regime) the system's state variables
2) The controlled variables: the excitation current $I_E[y]$, the turbine's blade pitches (at synchronous and asynchronous generator) $K_{TGS}[w]$ and $K_{TGA}[w]$, will be determined from the voltage and frequency values.
Practically, the control algorithm implementation involves:
1st step: the initial value establishment
For $R \to \infty$, $x \to 0$ and $U_N = 6000V$, $\omega_N = 314 rad/s$ $f_N = 50Hz$ there is solved the equation system (13)-(25), obtaining the following values for the controlled variables:

$$\begin{aligned} I_E &= y = 25.99766026 \\ K_{TGS} &= w = 1.825632299 \times 10^{-4} \\ K_{TGA} &= v = 1.825632299 \times 10^{-4} \end{aligned} \tag{26}$$

2nd step: the determination of perturbing elements values: R and T from the values of $U \neq U_N$ and $f \neq f_N$. For example, at a reactive and active power load, the system's voltage and frequency drops to: $U = 5800V$, $\omega = 307{,}7 rad/s$ ($f = 49Hz$)
There is solved the modified system with the above calculated values and with the previous controlled variables (26):

$$\begin{aligned} I_E &= y = 25{,}99766026; \\ K_{TGS} &= w = 1{,}825632299 \cdot 10^{-4}; \\ K_{TGA} &= v = 1{,}825632299 \cdot 10^{-4} \end{aligned} \tag{27}$$

There result two values for the impedance load (the perturbing factor):

$$\begin{aligned} \underline{Z_1} &= R + jX = R + J\omega T = \\ &= 5.61963048 \times 10^{-4} - j22.92018482 \end{aligned} \tag{28}$$

$$\begin{aligned} \underline{Z_2} &= R + jX = R + J\omega T = \\ &= 12.09313246 + j3362.255952 \end{aligned} \tag{29}$$

With these two values, the functioning can take place for a resistive-capacitive load (the Z_1 case), and respectively for a resistive-inductive load (the Z_2 case). In the paper there was considered the case of a resistive-inductive load (the Z_2 case).

3rd step: the determination of the controlled variables: I_E, K_{TGS}, K_{TGA} is performed for the system load (R and X):

The solution is:

$$\begin{aligned} I_E &= y = 26.36184252 \\ K_{TGS} &= w = 1.952922312 \times 10^{-4} \\ K_{TGA} &= v = 1.952922312 \times 10^{-4} \end{aligned} \tag{30}$$

4th step: the solving of the differential equations (1)..(11).
There is considered the following load

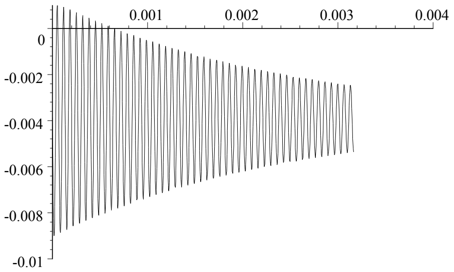
$$\begin{aligned} \underline{Z_2} &= R + jX = R + j\omega T = \\ &= 12.09313246 + j3362.255952 \end{aligned} \tag{31}$$

and with the previously controlled variables: I_E, K_{TGS}, K_{TGA} the equations (1)…(11) that defines the transient functioning regime can be solved. These obtained equations are used in the following simulation study cases.[4] [5]

4 Study cases – simulation results

The numerical values used in simulations are:
$R_d = R_q = 0$, $L_d = L_q = 0{,}2[H]$, $M_E = 0{,}98[H]$
$M_D = 0{,}08[H]$, $M_Q = 0{,}05H]$, $R_E = 5[\Omega]$, $L_E = 6[H]$
$M_{ED} = 0{,}4[H]$, $R_D = 0{,}5[\Omega]$, $R_Q = 0{,}1[\Omega]$,
$\omega_{0AG} = 628[rad/s]$, $\omega_{0SG} = 628[rad/s]$, $R_1 = 0$,
$L_1 = 0{,}6[H]$, $L_2 = 0{,}7[H]$, $M = 0{,}5[H]$, $R_2 = 0{,}65[\Omega]$
$J = 2[kgm^2]$

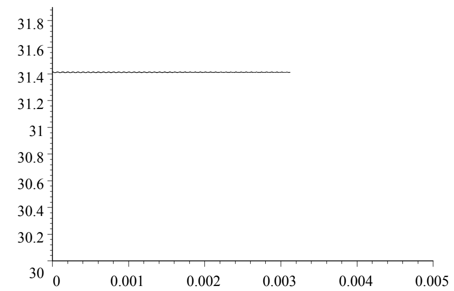
In figures 3 up to 9 there are presented the simulation results, for the both types of generators (asynchronous and synchronous). There can be noticed the overall good performance of the considered genset system.



$$i_{q(\infty)} = -3{,}95 \cdot 10^{-3}$$

Figure 3. I_q stator current evolution (asynchronous generator).

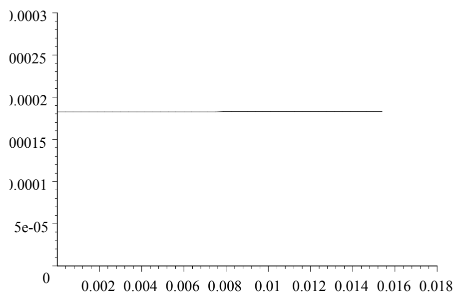
The stator current from the q-axis of the asynchronous generator are settled to the steady state regime value through an oscillating process.



$$i_{d(\infty)} = 31{,}84$$

Figure 4. I_d stator current evolution (asynchronous generator).

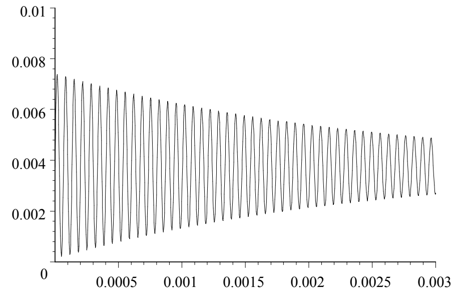
The stator current value from the d-axis of the asynchronous generator is slightly modified during the transient.



$$K_{TGA(\infty)} = 2 \cdot 10^{-4}$$

Figure 5. Torque evolution (asynchronous generator).

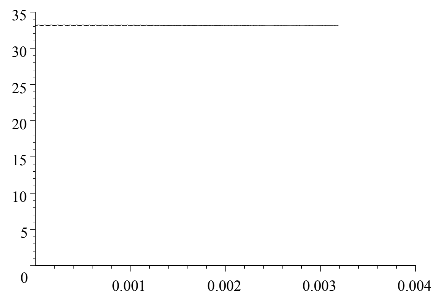
The torque constant has a similar value to the initial one due to the fact that the load drop was insignificant.



$$i_{qr(\infty)} = 0{,}004$$

Figure 6. I_{qr} rotor current evolution (asynchronous generator).

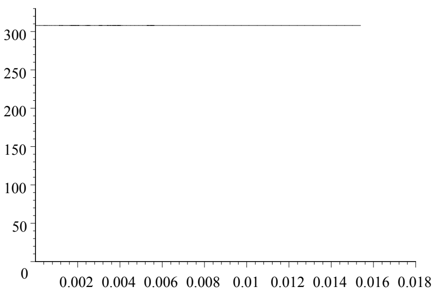
The rotor current from q-axis presents important oscillations meanwhile the transient process.



$$i_{d(\infty)} = 33{,}63$$

Figure 7. I_d stator current evolution (synchronous generator).

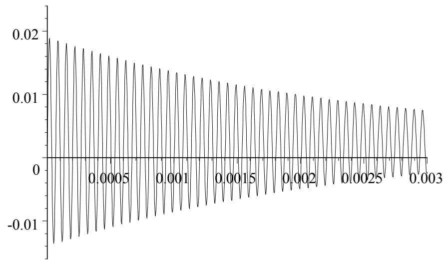
The stator current from d-axis is slightly modified in comparison to the stator current from the q-axis (as it can be noticed by comparing the figure 6 and 8).



$$\omega_{(\infty)} = 314$$

Figure 8. Angular velocity evolution (synchronous generator).

The angular velocity, respectively the synchronous generator's frequency is restored to the nominal value by modifying the synchronous generators torque.



$$I_{q(\infty)} = 2{,}35 \cdot 10^{-3}$$

Figure 9. I_q stator current evolution (asynchronous generator).

The final values for stabilization regime are obtained based on an algebraic equation system like (13)…(25).

The obtained solutions are the following:

$s = -4.890115419 \times 10^{-7}$
$g = 31.84490785$
$v = 1.952922312 \times 10^{-4}$
$a = -3.953409685 \times 10^{-3}$
$c = 0.00380578813 \times 10^{-3}$
$z = 33.62927686$
$b = -1.642897827 \times 10^{-7}$
$\omega = 317.7085164$
$x = 2.345758732 \times 10^{-3}$
$w = 1.952922312 \times 10^{-4}$
$m = 131.8$
$y = 26.36$

5 Conclusions

The time evolution of the system's main variables (currents, voltages, frequencies) can be obtained through the orthogonal axis generator's modeling (asynchronous generator and synchronous generator parallel connected). The controller's parameter tuning (two controllers for synchronous generator - excitation and the generator's driving turbine, and one controller for asynchronous generator – the generator's driving turbine) allows the obtaining of the desires responses, the voltages and frequency being restored to nominal values within an imposed time. The amortization's winding parameters influence the period of the transient. From the simulation results there can be estimated the value of the load stress (current, voltage and frequency modifications) with direct implication in the electro mechanic system's design.

The proposed model can be further extended at systems constituted out of several asynchronous and synchronous generators, and can be used in stability analysis of energetic power systems.

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