

MATLAB / SIMULINK MODEL OF A SYSTEM FOR DETERMINING THE ANGLE OF INTERNAL SYNCHRONOUS GENERATORS

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This paper deals with a Matlab / Simulink original system for determining the internal angle of high power synchronous generators, when they operate under electrical charge. Knowledge the load angle value at steady state and dynamic operation conditions have a great significance for the generator operating conditions. The system presented in this paper provides the user simulation models of synchronous generators in Matlab / Simulink and a friendly graphical interface for viewing and reading results.

Keywords: synchronous generator, internal angle, Matlab/Simulink model, Graphical User Interface (GUI)

1. Introduction

Modeling synchronous generators when they operate in stationary or dynamic regime, is currently widely used due to obvious advantage which modeling the excitation - generator - load system offers in different operating conditions of the generator.

Study on the model of the whole system behavior allows predetermination of actual functioning of both steady and transient regime for different electric charges of the generator.

The manner in which are modeled in Matlab / Simulink both the proper generator and the excitation systems and its electrical charge is not unique, even if the mathematical model of the generator remains the same.

Knowing the internal angle (often called "load angle") of a high power generator is important for its use in practice.

An accessible method of calculating the generator internal angle is to use the newer package SimPowerSystems of Matlab/Simulink computing environment. However there are other methods for determining the internal angle through simulation methods not using this medium [1], ..., [4]. This is why the system model for determining the internal angle was designed and implemented (which

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makes the subject of this paper). Furthermore, it was described a friendly graphic mode for presenting simulation results.

To verify the suggested method for determining the internal angle, we can apply a simple experimental method called stroboscopic method [5], with the aid of which it can be measured the internal angle when the electric charge is present and the generator works in a steady regime. The distinct errors between the two methods can also be calculated. It can be assumed that the errors of determining the internal angle during dynamic functioning regimes of the generator vary between the same limits when the simulation method proposed in this paper is used. Experimental determination of this angle is more difficult during dynamic functioning regimes than in stationary regime. Therefore the method proposed in this paper is preferred for dynamic regimes.

2. Method's principle

For a synchronous drowned pole generator in steady state, phase voltages equation is of the form [6]:

$$\underline{U} + R\underline{I} + jX_{\sigma}\underline{I} = \underline{E} + \underline{E}_0 + \underline{E}_a, \quad (1)$$

where: U - voltage across the phase winding, R - ohmic resistance of the winding phase, I - load current, X_{σ} -leakage reactance, E - induced voltage resulting magnetic flux in the air gap, E_0 - induced e.m.f. by the excitation flux, E_a - e.m.f. corresponding to reaction flux produced by the load current, because:

$$\underline{E}_a = -jX_a\underline{I}, \quad (2)$$

where X_a is dispersion reactance corresponding to reaction flux, equation (1) can be written as:

$$\underline{E}_0 = \underline{U} + R\underline{I} + j(X_{\sigma} + X_a)\underline{I} = \underline{U} + R\underline{I} + jX_s\underline{I}, \quad (3)$$

where $X_{\sigma} + X_a = X_s$ synchronous reactance of the machine.

Equations (1) and (3) corresponding phase diagram in Fig. 1 [6].

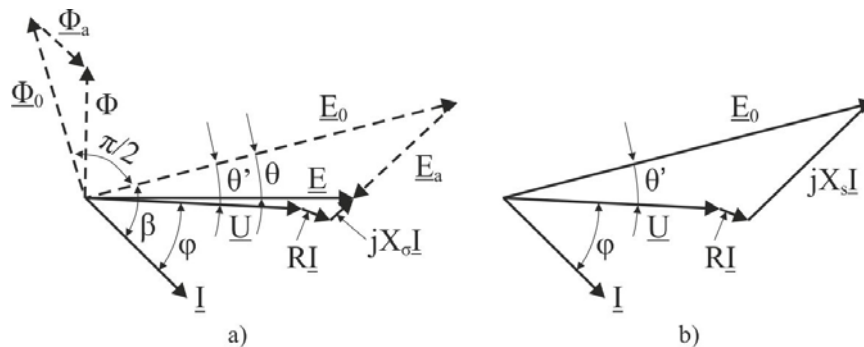


Fig. 1. Phasor diagrams for drowned pole generator:
a) the primary form (1); b) – shorted form (3).

The ohmic resistance of the phase winding R , at high power generators, is much smaller (several hundred times) than synchronous reactance X_s , because as the machine increases its power, load current increases. Increasing load current increases section windings conductors and consequently leads to a lower ohmic resistance.

In conclusion, the result is the simplified phasor diagram shown in Fig. 2.

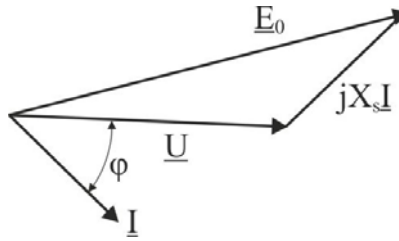


Fig. 2. Simplified phasor diagram of synchronous generator.

Voltage drop dispersion reactance $X_\sigma I$ is also negligible compared to the terminal voltage U , which allows to write [6], [7]:

$$\underline{U} \approx \underline{E} . \quad (4)$$

Equation (4) expresses that the resultant e.m.f. E produced by the magnetic field resulting from the synchronous generator is approximately equal to the phase voltage U , measured at the generator stator terminals.

On the other hand, the phase shift angle between no-load e.m.f. \underline{E}_0 and terminal voltage U is practically equal to the angle θ between \underline{E}_0 and E , that means internal angle (load angle) of the machine.

In no-load operating mode where $I = 0$, all sags are zero, the armature reaction magnetic field is zero and therefore:

$$\underline{U}_0 = \underline{E}_0 . \quad (5)$$

The previously presented leads to the conclusion that *the internal angle of the machine can be determined by measuring the phase difference between idling voltage U_0 and load operating voltage U .*

3. Model

The calculation system of internal angle is shown in Fig. 3. This model was designed based on an existing synchronous generator model found in the SimPowerSystems package, part of Matlab/ Simulink software. I have considered the same synchronous machine, also the same operating parameters for results comparison between SymPowerSystems package example model and designed system. Thus is made, I have obtained correctness demonstration of results, using proposed model in this paper.

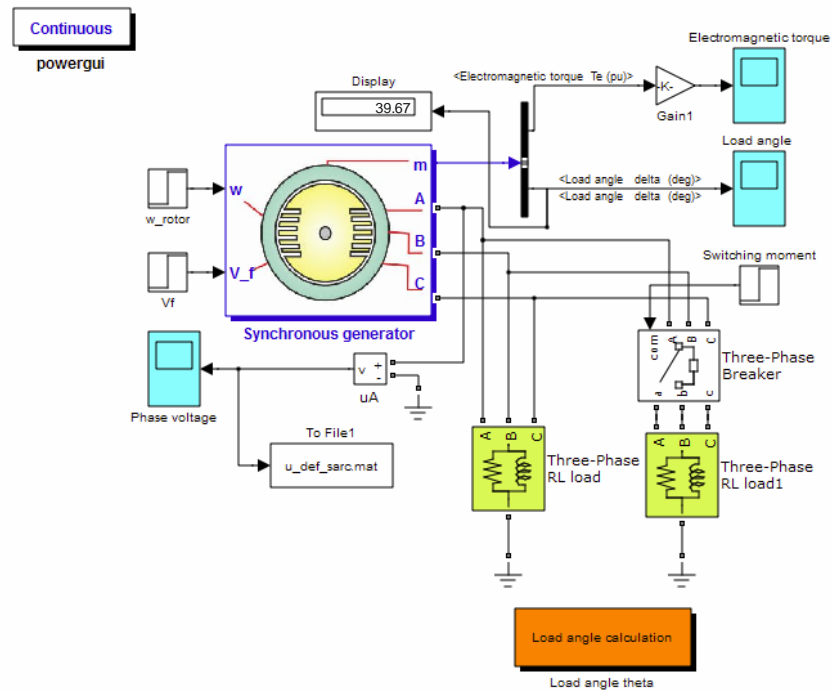


Fig. 3. Model that realizes the generator internal angle calculation.

The synchronous turbogenerator around which it was build the calculation system from SimPowerSystems has its parameters illustrated in Fig. 4.

Configuration	Parameters	Advanced
Nominal power, line-to-line voltage, frequency [Pn(VA) Vn(Vrms) fn(Hz)]:		
[2e+006 400 50]		
Reactances [Xd Xd' Xd'' Xq Xq' Xl] (pu):		
[2.11 0.17 0.13 1.56 0.23 0.05]		
d axis time constants:	Short-circuit	
q axis time constants:	Short-circuit	
Time constants [Td' Td'' Tq''] (s):		
[0.33 0.03 0.03]		
Stator resistance Rs (pu):		
0.0095		
Pole pairs p ():		
2		
Initial conditions [dvr(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) vf(pu)]:		
0 -90 1.04167e-013 1.04167e-013 1.04167e-013 0 -120 120 8.33333e-005		

Fig.4. Synchronous generator parameters.

Dimensionless value of excitation voltage V_f (pu) of Fig. 4 is the initial value of these parameter and not its value in nominal regime.

Theoretically this initial value should be zero, but this leads to errors in Matlab and therefore a very little value: $V_f = 8.333\text{e-}5$ was chosen for initial excitation voltage.

This value is taken into account only when $t = 0$, when the chosen calculation method's instructions start. For this reason in Fig. 5 exist the block V_f , which requires the excitation voltage to the nominal ($V_f = 1$).

Block made a jump from baseline voltage $V_f = 8.333\text{e-}5$ [p.u.], to the final value $V_f = 1$ [p.u.], as shown in Fig. 5.

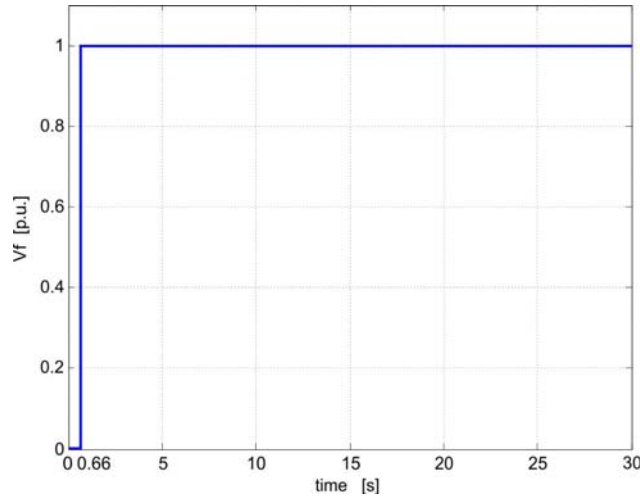


Fig. 5 Variation in time of excitation voltage generator during simulation (30 s).

Maintaining the interval for excitation voltage at baseline value $V_f = 8.333\text{e-}5$ equal to $\Delta t = 0.66\text{s}$ (Fig. 5), after the excitation voltage jumps from this value to the final nominal value ($V_f = 1$). The size of the time step Δt is imposed by the numerical method used to solve differential equations: Solver – *odes 14x (Extrapolation)*.

The numerical model presented is designed to operate at constant rotor speed and constant excitation current, both having nominal values. Generator output is connected to two load blocks "Three-Phase RL load" and "Three-Phase RL load1". "Three-Phase RL load1" block is connected to the generator output through a three phase contactor, its functioning being controlled by "Switching time" block. This block allows connection to load set through specifying block parameters "Three-Phase RL load1" when the model's user decides. Usually, changing the electric charge at which the generator functions is recommended to be done after finishing the starting transient regime. The two blocks system of

electric charge and the contactor – switching time ensemble allows operation model in three distinct situations:

- No load operating generator through the entire simulation period;
- Load operating generator during the entire simulation period;
- Starting the generator in a certain load regime and at time t , if the user desires, the charging regime can be modified.

The model shown in Fig.3 also contains "uA" block which allows phase voltage measurement for every generator load regime.

Viewing internal angle value by means of model's intrinsic value is made with "Display" block.

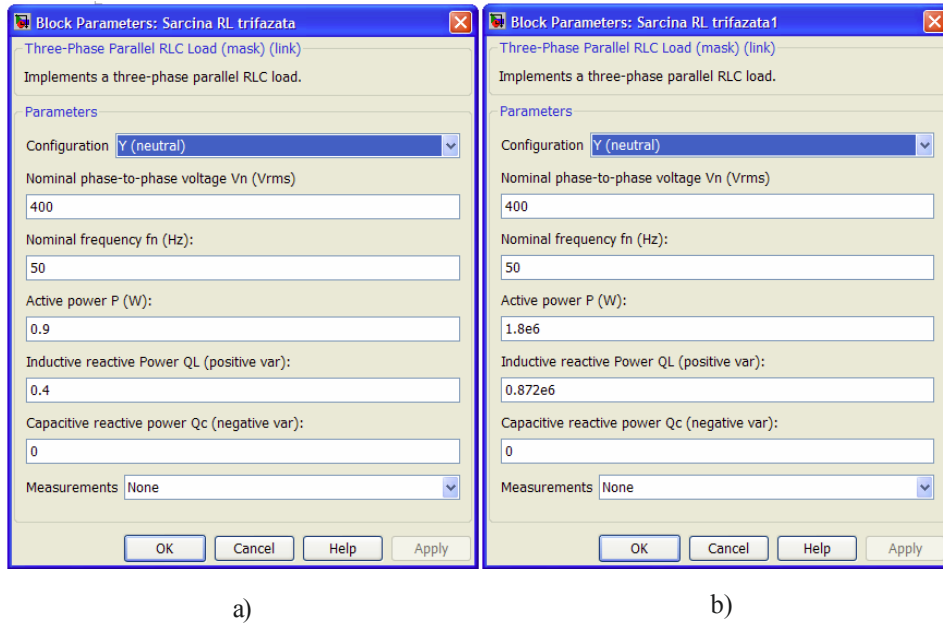


Fig. 6. Load parameters: a) – no load; b) – nominal load.

To determine the internal angle through the proposed method, proceed as follows:

A. It simulates no-load generator functioning throughout the entire simulation period, by setting " Three-Phase RL load " block parameters (Fig. 6,a). Simulation results (phase voltage at no load) are stored in the file "*u_def_gol.mat*".

B. It simulates the generator functioning in nominal load throughout the entire simulation period by setting " Three-Phase RL load1 " block parameters (Fig. 6,b). Simulation results (rated load voltage phase) are stored in the file "*u_def_sarc.mat*".

C. After running the simulation with the two conditions, GUI is called by double clicking on the "Calculate internal angle" block. Through this operation the process starts calculating the internal angle and the graphical presentation in the same coordinate system of the two phase voltages: no-load and nominal load.

Statement The internal angle calculated with SimPowerSystems's model generator is denoted by "delta", but to distinguish the internal angle calculated by the method proposed in this paper, the latter was noted by "theta" according to those presented in Section 2.

By double clicking on "Calculate internal angle" block, the GUI appears in Fig. 7.

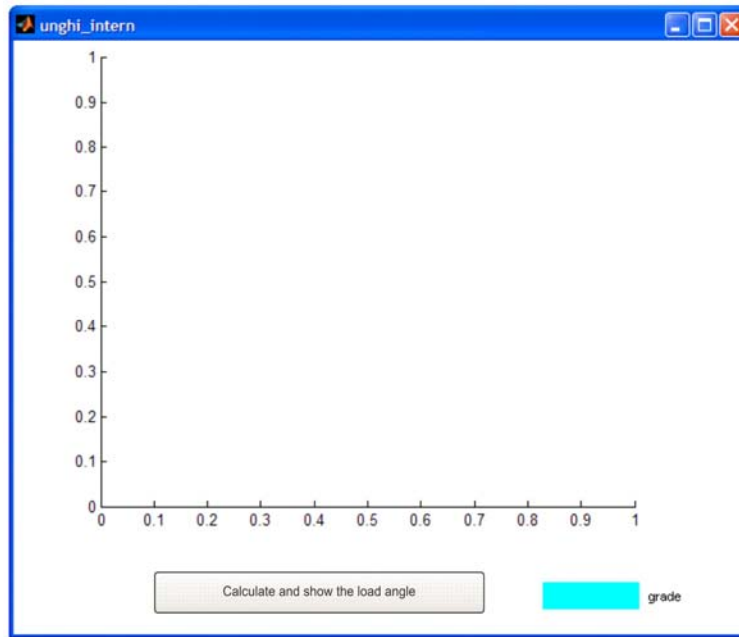


Fig. 7. Graphical interface that displays the waveforms of voltages and phase angle of phase shift value.

"Calculate internal angle" block, calling Matlab script file "unghi_intern.m", whose structure is shown below.

unghi_intern.m

```
function varargout = unghi_intern_teza(varargin)
% Begin initialization code
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', @unghi_intern_OpeningFcn, ...
```

```

        'gui_OutputFcn', @unghi_intern_OutputFcn, ...
        'gui_LayoutFcn', [], ...
        'gui_Callback', []);
    if nargin && ischar(varargin{1})
        gui_State.gui_Callback = str2func(varargin{1});
    end
    if nargin
        [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
    else
        gui_mainfcn(gui_State, varargin{:});
    end
% End initialization code - DO NOT EDIT
function unghi_intern_OpeningFcn(hObject, eventdata, handles, varargin)
handles.output = hObject;
guidata(hObject, handles);
function varargout = unghi_intern_OutputFcn(hObject, eventdata, handles)
varargout{1} = handles.output;
% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
cla;
load u_def_gol;
load u_def_sarc;
S=size(udg);
[maxNumCol, maxIndexCol]=max(S);
N=maxNumCol-1;
t_f=max(udg(1,:));           % Simulation time as follows;
p=t_f/N;                     % Step simulation;
f=50;                         % Generator voltage frequency;
T=1/f;                        % Voltage generator period;
np=T/p;                       % Number of points defining a period;
Ds=N*np;                      % During simulation;
M=29;                          % At the start of plotting;
Ri=M/p-1;                     % Rank of starting simulation;
Rf=Ri+np;                     % Rank in the simulation ends;
ag=udg(2,Ri:Rf);              % Define no load voltage vector 'u_def_gol';
mx=max(ag);                   % The maximum gap voltage;
[num idx]=max(ag);             % Identifying position while the maximum gap voltage;
[xg yg]=ind2sub(size(ag),idx); % Position while the maximum;
bg=udg(1,Ri:Rf);              % Defining the vector for the 'u_def_gol';
bg(yg);                       % When they get maximum tension on empty;
as=uds(2,Ri:Rf);
mxs=max(as);
[nums idxs]=max(as);
[xs ys]=ind2sub(size(as),idxs);
bs=uds(1,Ri:Rf);
bs(ys);
delta_t=bs(ys)-bg(yg);        % Phase shift in time;
delta =delta_t*360/T           % Phase angle in degrees;
plot(udg(1,Ri:Rf),udg(2,Ri:Rf),uds(1,Ri:Rf),uds(2,Ri:Rf),'linewidth',2)
xlabel('timp [s]')

```



```

ylabel('u-gol, u-sarcina [V]')
legend('u-gol', 'u-sarc', 'Location','NorthEast')
set(handles.rez_delta,'string',delta); %Display delta

```

4. Representation of internal tensions and display angle value

For waveform representation of no-load phase voltages and load phase voltages, data is stored in the "mat" file, we click on the "Compute and display the angle internal angle" button. This action will cause the GUI to show the waveforms of both tensions and the internal angle's value as shown in Fig. 8.

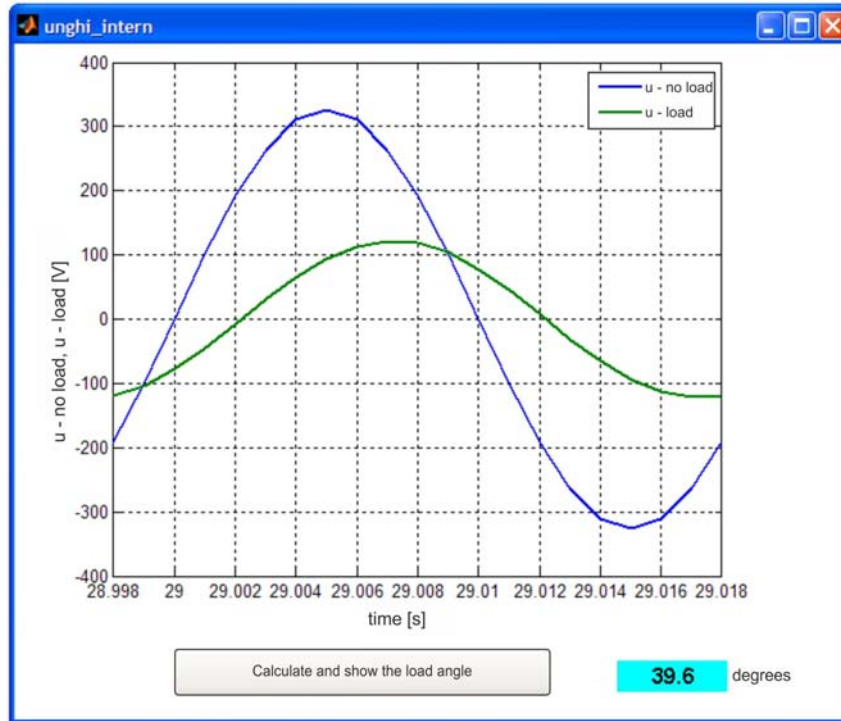


Fig. 8. Waveform display of both voltage and internal angle value.

6. Conclusions

Fig. 8 displays the internal angle value obtained by calculating the phase difference between no-load phase voltage and phase voltage under load, which confirms the internal angle obtained with SimPowerSystems's model ("Display" block in Fig. 3). Internal angle calculation using proposed method in the paper, is actually δ' , means phase shift angle between no-load phase voltage u -gol and phase voltage under load u -sarc. (Fig. 8).

We have found internal angle value, based on proposed method in this paper, slightly smaller than the real value obtained from SimPowerSystems. It follows developed method in this work means internal angle calculation δ' with some errors. Calculated error is 0.17%, between these two methods of internal angle calculation δ' , if we consider SimPowerSystems method as reference.

Internal angle calculation for original method has the advantage of short computation time. It is important to know by machine operator, what is the computation error between internal angle δ' comparing with real internal angle δ .

This leads to the conclusion that the original system for measuring the internal angle, covered by this paper, is accurate and reliable and can be applied to synchronous generator models that are not equipped with such a system. Comparative presentation of internal angle values obtained by two different methods, provide a guarantee for using the system in any modeling synchronous generator ensemble with accuracy imposed by the conditions of the operating modes of the generator.

R E F E R E N C E S

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