Synchronous Generator Load Angle Estimation
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Abstract— In the paper is proposed a load angle estimation method for synchronous generators. The estimation method is based on synchronous generator corresponding voltage-current vector diagram and parameters of generator, transformer and transmission lines. In addition measurement of the load angle is presented. The estimation results were compared with the measured ones. The estimation method gives satisfactory accuracy for load angles less then 120° el. Although the load angle is a key variable for generator stability, it is rarely used as a variable in excitation control system, because the measurement problems. Hence, this estimation method has a wide area of application in excitation systems for control algorithm and to provide stable work of synchronous generator in capacitive operating area.

I. INTRODUCTION

A synchronous generator connected to an AC system has to remain in synchronism even in some extreme situations that can appear in operating conditions not exceeding the range of allowable loading. The exceeding of allowable loading would cause the activation of generator protection and disconnection of a synchronous generator from an AC system. This could cause (depending on the state of an AC system) disconnection of other aggregates from an AC system. Automatic voltage regulators of synchronous generators have the excitation current limitations dictated by P-Q diagram (fig. 1). This enables optimal utilization of generator loading and safer work of a generator operating in parallel with an AC system [1], [2], [3].

Fig. 1. Limitations in the P-Q diagram of the synchronous generator

Excitation current limitations are based on P-Q diagram of a synchronous generator. These limitations are not a substitution for the generator protection activated in some extreme situations when allowable loading is exceeded. When these limitations are reached, the voltage regulator is turned off. Then the stator current limitations in over-excitation and under-excitation operating modes of a synchronous generator as well as minimal and maximal excitation current limitations (instantaneously and with the time delay) are turned on [4], [5].

Under-excitation (capacitive) operating mode of a synchronous generator appears in systems with under-loaded long power transmission lines, by connecting long power transmission lines to voltage and by asynchronous work of regulating transformer regulators. Minimal excitation current limitations limit the load angle and a generator will not lose synchronism [6], [7].

Load angle of a synchronous generator is the key variable for determining of stable work of the synchronous generator on AC network. In this paper is proposed a load angle estimation method for synchronous generator connected over transformer and transmission line to AC network (fig. 2).

II. LOAD ANGLE ESTIMATION

For load angle estimation voltage-current vector diagram is used (fig. 3.), where δ₁ is the angle between induced voltage $E_0$ and generator voltage $U$, δ is the load angle between induced voltage $E_0$ and AC network voltage $U_ac$, I is the armature current, R is the equivalent resistance of stator, transformer and transmission line, $X_e$ is the equivalent reactance of the transformer and transmission line and $X_q$ and $X_d$ are synchronous generator reactances.

In [2] is proposed the estimation method based only on the quadrature-axis synchronous reactance $X_q$ and equivalent resistance $R$, whereas method proposed in this paper includes in addition the equivalent reactance of the transformer and transmission line $X_e$.  

Fig. 2. Synchronous generator connected to AC network
From diagram on fig. 3, load angle is obtained

\[ \delta = \arctg \frac{I \cdot X_q \cdot P - I \cdot R \cdot Q + X_e \cdot I \cdot P}{U_m \cdot S + I \cdot R \cdot P + X_q \cdot I \cdot Q + X_e \cdot I \cdot Q} \]  

(1)

where \( \delta \) is the load angle, \( I \) is the armature current, \( P \) is the active power, \( Q \) is the reactive power and \( S \) is the apparent power.

The values of the quadrature-axis synchronous reactance \( X_q \), equivalent resistance \( R \) and reactance \( X_e \) must be known for this estimation method.

III. EXPERIMENTAL VERIFICATION OF LOAD ANGLE ESTIMATION METHOD

For the implementation purposes of load angle estimation method and excitation regulation it was developed digital control system (fig. 4) based on DSP ADMC300 [8]. It was developed graphical oriented software tool. This software tool includes graphical interface for easier modelling of control algorithms. For testing purposes software monitoring tool was also developed. It enables regulator parameters optimizing as well as displaying and recording of testing results via a PC. Experimental setup is presented on the fig. 5.

A. Load angle measurement

The load angle was measured by an incremental encoder generating 5000 impulses per rotor rotation and device, which structure is presented on the fig. 6. The load angle is measured at the exact moment of passing through zero of the network’s phase voltage, which means that for the power system’s frequency of 50 Hz the sampling frequency is 100 Hz. The angle is measured based on the difference between the momentary position of the rotor and the network phase voltage.

When network’s phase voltage passing through the zero, a stop is generated and the device remembers the rotor position. The rotor position is saved in the timer variable; the timer being set as an external tact counter. The counter is reset when the zero marker touches zero. The resolution of load angle measuring depends is in this case 0.36° electrical. The output constant of the load angle is 54.25 mV/° electrical.
B. Static accuracy of load angle estimation

The analysis of load angle estimation static accuracy via tree appropriate experiments is done. The measured and estimated results are compared. Active power is changing from zero to 100% of nominal value with the step change of 20%. The results of these comparisons are showed on the figures 7, 8 and 9.

In the first experiment (fig. 7), reactive power of the generator is zero. In the second experiment (fig. 8) the reactive power is inductive (100% of nominal power) and is kept constant in the whole range of active power changing. In the third experiment (fig. 9) reactive power is capacitive and is kept constant (100% of nominal power).

In the whole range of active power changing, the error of load angle estimation is less then 4° el.

C. Dynamic accuracy of load angle estimation

The comparison of estimated results with measured ones via three appropriate experiments is done. There is active power step change (at the moment \( t = 1s \)) from zero to 100% of nominal power and again to zero after four seconds (fig. 10). The reactive power is kept constant via reactive power controller in all these experiments. In the first experiment (figures 11 and 12), the reactive power is near zero.

In the second experiment the generator is in inductive operating mode and reactive power is 100% of nominal power. (figures 13 and 14).
The difference of measured and estimated load angle (° el.)

Fig. 14. The difference of measured and estimated load angle with 100% inductive reactive power and step change of active power

In the third experiment (figures 15 and 16) the generator is in capacitive operating mode and loses synchronism. Measured and estimated results show good correspondence except near the moment when generator loses synchronism. In that moment the voltage-current vector diagram used as a base in the presented estimation method, is not valid. For algorithms that need to keep a generator in stable operating mode, it is relevant operating range with load angles less than 90° el. So, if excitation control algorithm ensures stable operating mode of a generator, load angle will never exceed 90° el.

Parameters needed for the load angle estimation are quadrature-axis synchronous reactance $X_q$, equivalent resistance $R$ and reactance $X_e$. Errors in determining these parameters can appear because of incorrect initial estimated values and because of their dependence of operating conditions (temperature increase and iron saturation). An estimation method dependence of parameters determining accuracy is analyzed in capacitive operating mode with constant reactive power (100% of nominal power). The results of this analysis show that static accuracy of presented estimation method is practically independent of errors in determining stator resistant. The average absolute dynamic error is less then 1% in conditions of stator resistance change. So, the determining accuracy of stator resistant value has not a great influence on the accuracy of presented load angle estimation method. However, errors in determining reactances $X_q$ and $X_e$ influence on the accuracy of this load angle estimation method. The average dynamic absolute error depends of $X_q$ and $X_e$ change.

IV. CONCLUSIONS

An accuracy of presented load angle estimation method depends of voltage and current measurement accuracy as well as of parameters determining accuracy (quadrature-axis reactance $X_q$, equivalent resistance $R$ and reactance $X_e$). Presented estimation method gives accurate enough results for load angles less than 90° el. Excitation control system with additional signal, estimated load angle, can improves the stability of a synchronous generator in capacitive operating mode. Future research will be based on development of excitation control algorithms based on the estimated load angle of a synchronous generator.

APPENDIX A

The nominal data of the synchronous generator and transmission line are listed below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_n$</td>
<td>400 V</td>
</tr>
<tr>
<td>$I_n$</td>
<td>120 A</td>
</tr>
<tr>
<td>$S_n$</td>
<td>83 kVA</td>
</tr>
<tr>
<td>$f_n$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>600 rpm</td>
</tr>
<tr>
<td>$\cos \phi_n$</td>
<td>0.8</td>
</tr>
<tr>
<td>$U_{fn}$</td>
<td>100 V</td>
</tr>
</tbody>
</table>
I_{in} \quad 11.8 \text{ A} \\
X_d \quad 0.8 \text{ p.u.} \\
X_q \quad 0.59 \text{ p.u.} \\
X_e \quad 0.2 \text{ p.u.} \\
R \quad 0.01 \text{ p.u.} \\

REFERENCES


