LOAD ANGLE ESTIMATION OF A SYNCHRONOUS GENERATOR

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***Abstract*— This article is focused on the load angle estimation method of a synchronous generator for the purposes of the regulation in synchronous generator excitation systems. The estimation is based on the real parameters of a synchronous generator, which are given by the corresponding voltage-current vector diagram. The estimation results of the load angle are compared with the measured ones. Presented estimation method gives satisfactory accuracy compared with the measured results for the load angles less then 120º el. The adding of the load angle regulation in an excitation system, results in an improvement of the stability of a synchronous generator operating in a capacitive mode.**

Keywords – load angle estimation, synchronous generator, excitation system

I. INTRODUCTION

A synchronous generator which is connected to an AC system has to remain in synchronism even in some extreme situations that can appear in the operating conditions keeping a generator in the range of permissible loading. In the real system, the exceeding of allowed loading would cause the activation of generator protection and disconnection of a synchronous generator from an AC system. In such cases, depending on the state of an AC system, it could cause disconnection of other aggregates from an AC system. Automatic voltage regulators of synchronous generators have the excitation current limitations as it is dictated by P-Q diagram. This enables optimal utilization of permissible loading and safer work of generator that is operating in parallel with a distribution network.

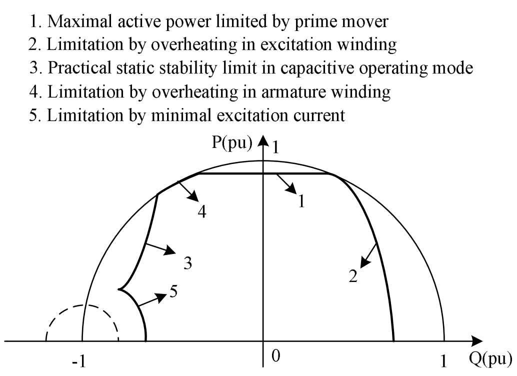

Figure 1. P-Q diagram of a synchronous generator including all limitations

The changes in reactive power are bigger as the power of network short circuit on the generator terminals is bigger and as the changes of network voltages are bigger.

Excitation current limitations are based on P-Q diagram of a synchronous generator (Fig. 1.). These limitations aren't a substitution for the generator protection which is activated in some extreme situations when permissible loading is exceeded. When these limitations are reached, the voltage regulator is turned off and the regulation of the limited variables is turned on. Regularly are used the limitations of stator current in over-excitation and under-excitation operating modes of a synchronous generator and the limitations of maximal (instantaneously and with the time delay) and minimal excitation current.

Under-excitation capacitive operating mode of a synchronous generator is appeared 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 limits of excitation current limit the load angle and the generator will not lose synchronism. These minimal limitations in excitation current can be done based on P-Q diagram of a synchronous generator (Fig. 1.) or by load angle regulation in under-excitation operating mode (Fig. 2.).

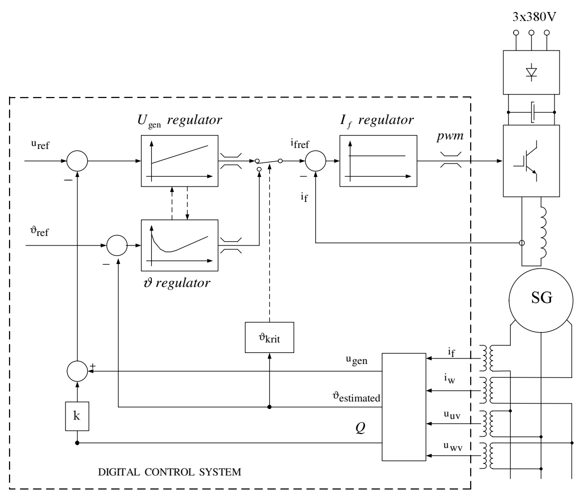

Figure 2. Structure of excitation regulation system with load angle regulator and load angle estimator

Presented solution in classical regulation structure includes the load angle regulator (Fig. 2.). When load angle is near its unstable value, the voltage regulator is turned off and the load angle regulator is turned on. In this situation load angle regulator sets the excitation current reference to its maximal value and on that way decreases the load angle so that generator remains in synchronism. So this regulation method enables stabile work of generator near the stability limits and expands the operating range of generator. This method requires knowing of the instantaneous load angle. To avoid additional sensor, the value of load angle is estimated by measuring of two generator voltages and two generator currents. For the purposes of determining the accuracy of the estimated value, load angle is measured via digital encoder.

II. LOAD ANGLE ESTIMATION

For load angle estimation is used voltage-current vector diagram (Fig. 3.).

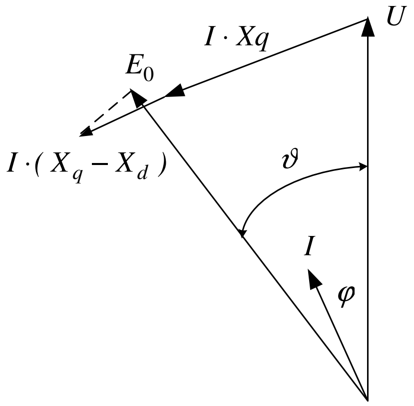

Figure 3. Vector diagram

From diagram on fig. 3. is obtained

$$\mathrm{tg}\vartheta = \frac{I \cdot X_q \cdot \cos\varphi - I \cdot R \cdot \sin\varphi}{U + I \cdot X_q \cdot \sin\varphi + I \cdot R \cdot \cos\varphi}, \qquad (1)$$

respectively

$$\vartheta = \mathrm{arctg}\frac{I \cdot X_q \cdot P - I \cdot R \cdot Q}{U \cdot S + I \cdot X_q \cdot Q + I \cdot R \cdot P}. \qquad (2)$$

Quadrature-axis synchronous reactance X_q is needed for this estimation method. Its value is well known from the producers and is not very dependent on saturation.

In situations when short circuit appears, generator voltage suddenly falls and generator current arises. In such situations, measuring equipment goes to saturation, and the measured results of active and reactive power are not reliable. The estimated value for load angle is not correct too. In such cases, the system forces the excitation current. The excitation current rises to its maximal value that is determined by its maximal limit. When short circuit appears, the load angle estimator sets the load angle to its maximal value and force the excitation current to its maximum limit. The load angle estimation algorithm is implemented in the developed digital system DIRES 21 [2] (Fig. 4.).

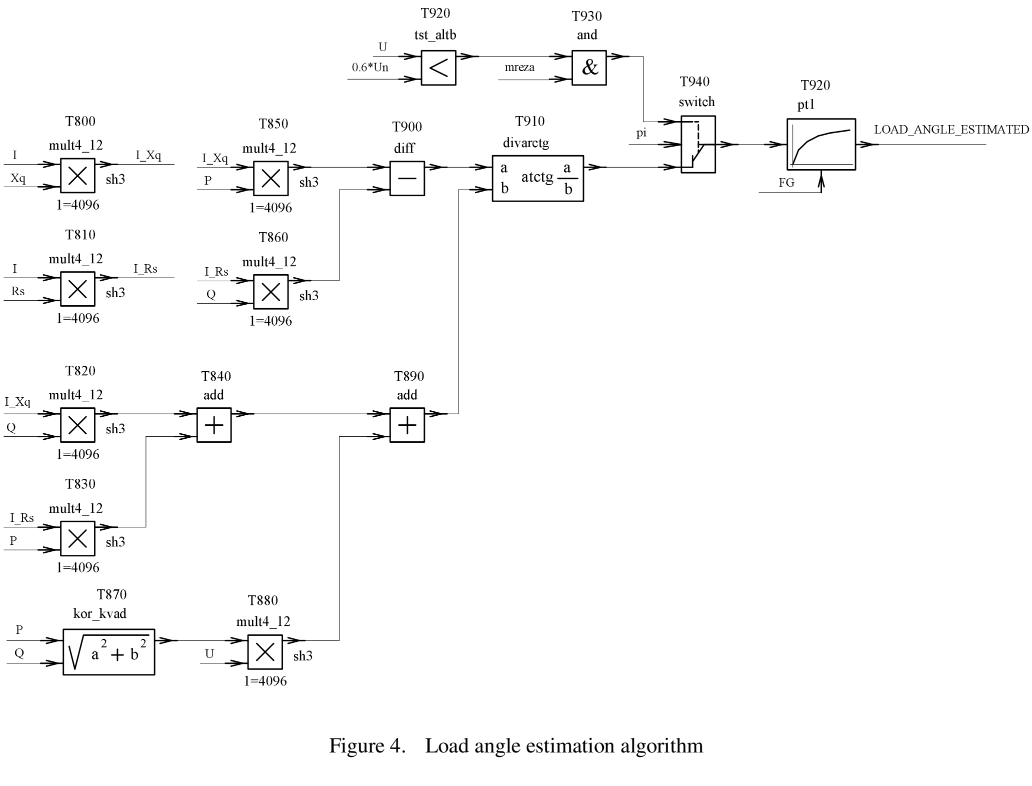

Figure 4. Load angle estimation algorithm

III. EXPERIMENTAL VERIFICATION OF LOAD ANGLE ESTIMATION METHOD

For implementation purposes of presented estimation method and excitation regulation it is developed four-processor digital system based on DSP ADMC300 [1]. This system includes software tool for algorithm modeling on a PC. This software tool includes graphical interface for easier modeling of the control algorithm just via blocks. For testing purposes, optimizing of the parameters of regulators and for displaying and saving the results of testing, it is also developed software tool so all the control and visualization of the control algorithm can be done just via a PC.

In this analysis of excitation regulation are used methods of mathematical analysis, simulation on PC and experimental verification on the laboratory model of the synchronous generator (75 kVA nominal power). The generator is via transformer connected to 10kV. Prime mover for this generator is a pair of dc motors with separate excitation which are fed by thyristor converters.

A. Static accuracy of load angle estimation

The analysis of static accuracy of load angle estimation is done via tree appropriate experiments. The measured and estimated results are compared. Active power is changing from zero to 100% of nominal value with the step of 20%. The results of these comparisons are showed on the figures 5, 6 and 7.

In the first experiment (Fig. 5.), reactive power of the generator is zero. In the second experiment (Fig. 6.) the reactive power is inductive and is kept constant in the whole range of active power changing. In the third experiment reactive power is capacitive and is kept constant, 100% of nominal power (Fig. 7.).

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

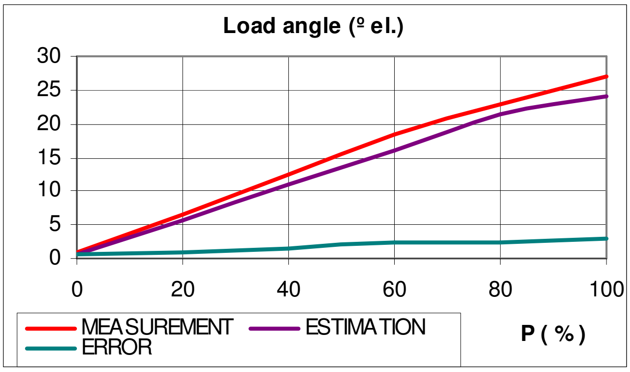

Figure 5. Measured and estimated load angle and estimation error with zero reactive power during active power changing from 0 % to 100% of nominal power

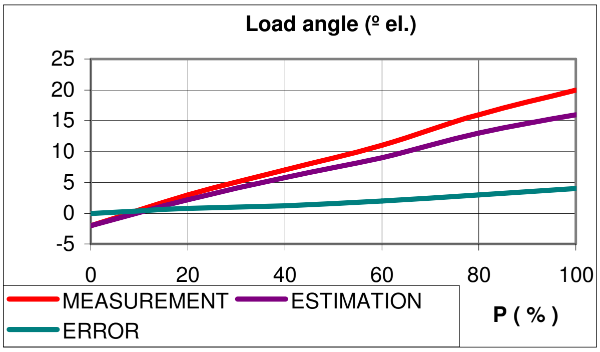

Figure 6. Measured and estimated load angle and estimation error with 100% inductive reactive power during active power changing from 0 % to 100% of nominal power

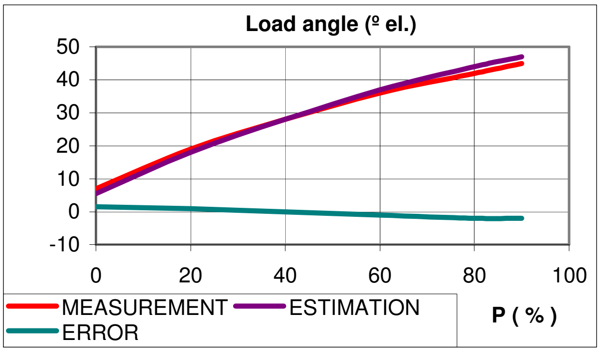

Figure 7. Measured and estimated load angle and estimation error with 100% capacitive reactive power during active power changing from 0 % to 100% of nominal power

B. Dynamic accuracy of load angle estimation

The comparison of estimated results with measured ones is done via three appropriate experiments. In these experiments there are step arise of active power (t = 1s) from zero to 100% of nominal power and again to zero after four seconds (Fig. 8.). The reactive power of the generator is kept constant via reactive power regulator in all these experiments. In the first experiment (Fig. 9.), the reactive power is kept near zero. In the second experiment generator is operating in inductive mode and reactive power is 100% of nominal power of the generator (Fig. 10.). In the third experiment generator is operating in capacitive mode and the reactive power is 100% of nominal power.

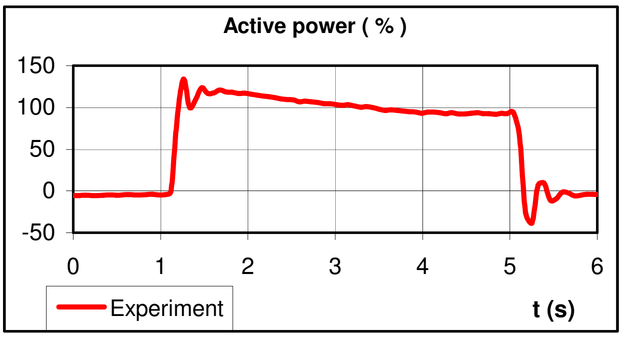

Figure 8. Active power of the tested synchronous generator

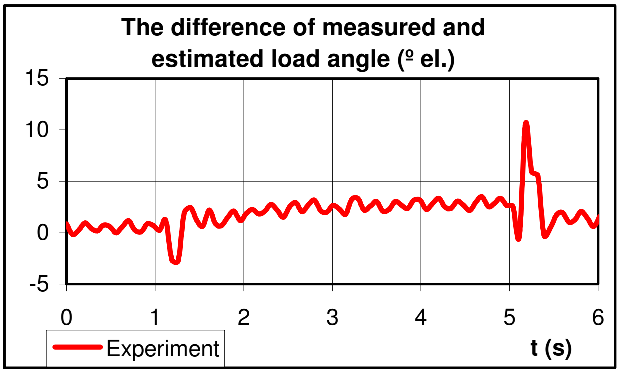

Figure 9. The difference of measured and estimated load angle with zero reactive power and step change of active power with included load angle regulator

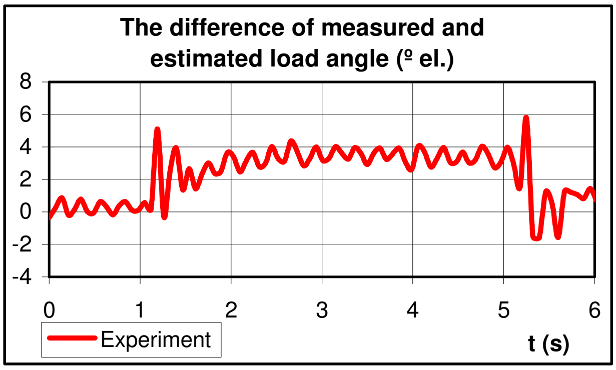

Figure 10. The difference of measured and estimated load angle with 100% inductive reactive power and step change of active power with included load angle regulator

First two experiments (Figs. 9, 10.) show good correspondence with the measured results. The averaged error of the estimation in all these three experiments is less then 2,5° el. and maximal error during load angle rise is 10° el.

In the third experiment (Fig. 11.) generator is operating in capacitive mode and lose synchronism. Measured and estimated results show good correspondence except near the moment when generator loses synchronism. In that moment the voltage-current vector diagram, which is used as the base in presented estimation method, is not relevant. For the algorithms that need to keep generator in stabile operating mode, it is relevant operating range for the load angles less then 90° el. So, if the presented algorithm is working well, load angle will never exceed 90° el.

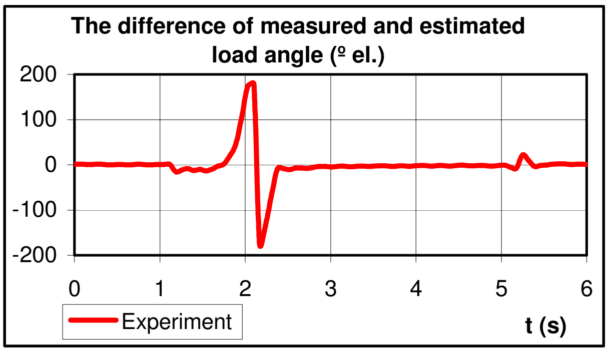

Figure 11. The difference of measured and estimated load angle with 100% capacitive reactive power and step change of active power with included load angle regulator

The parameters for load angle estimation are quadrature-axis reactance X_q and stator resistance R. The errors in determining these parameters can appear because of wrong initially used values and because of their changing in operating conditions (temperature and induction rise). The dependence of this estimation method on the accurate determining of these parameters is analyzed in capacitive operating mode with constant reactive power, 100% of nominal power. The results of this analysis show that presented estimation method is practically independent on errors in determining stator resistant. The average absolute error of the estimated load angle in dynamic conditions is less then 1% compared with the measured results in the conditions of stator resistance changing in estimator. So results of this analysis show that the accuracy of the estimated stator resistant value is not essential for the load angle estimation. However, errors in determining the reactance X_q influence on the accuracy of this load angle estimation method. The average absolute error in dynamic conditions rises with the changing of reactance X_q.

IV. CONCLUSIONS

The accuracy of the presented load angle estimation method of a synchronous generator depends on the chosen measuring method for currents and voltages of a synchronous generator and on parameters determining of a synchronous generator (quadrature-axis reactance X_q and stator resistance). These papers show that this estimation method gives accurate enough results for the load angles less then 90 °el. Excitation regulation system with additional load angle regulator improves the stability of a synchronous generator operating in capacitive mode.

SYMBOLS

ϑ - load angle of a synchronous generator

X_d , X_q – reactances of a synchronous generator

P – activer power of a synchronous generator

Q – reactive power of a synchronous generator

S – apparent power of a synchronous generator

U, I – voltage and current of a synchronous generator

φ - phase angle

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