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Tomislav Idžotić, Gorislav Erceg, Damir Sumina

Synchronous Generator Load Angle Measurement and Estimation

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Original scientific paper

The article is focused on a load angle measurement and estimation in excitation control systems of synchronous generator. Load angle is measured by digital encoder. The estimation method is based on synchronous generator parameters given by the corresponding voltage-current vector diagram. The estimation results were compared with the measured ones. The estimation method gives satisfactory accuracy for load angles less then 120° el. Load angle control in excitation systems improves the stability of a synchronous generator in capacitive operating mode.

Key words: digital control system, excitation system, load angle estimation, synchronous generator

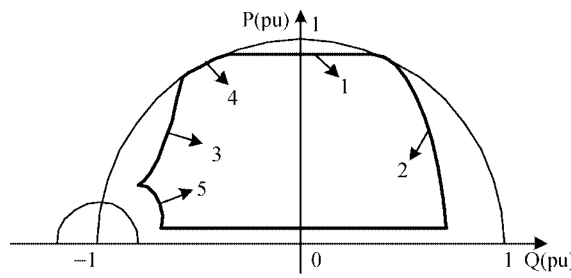
1 INTRODUCTION

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 controllers of synchronous generators have the excitation current limitations dictated by P-Q diagram. This enables optimal utilization of generator loading and safer work of a generator operating in parallel with an AC system.

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. In these conditions is a bigger danger of overloading (over-excitation operating mode) or of losing synchronism.

Excitation current limitations are based on P-Q diagram of a synchronous generator (Figure 1). These limitations aren't a substitution for the generator protection activated in some extreme situations when allowable loading is exceeded. When these limitations are reached, the voltage controller 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.

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 controllers. Minimal excitation current limitations limit the load angle and a generator will not lose synchronism. These minimal excitation current limitations can be realized by P-Q diagram of a synchronous generator (Figure 1) or by load angle control in under-excitation operating mode (Figure 2).



1. Maximal active power limited by prime mover
2. Limitation caused by excitation winding overheating
3. Practical static stability limit in capacitive operating mode
4. Limitation caused by armature winding overheating
5. Minimal excitation current limitation

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

Classical excitation control structure includes PI voltage controller superior to excitation current controller. In this control structure the load angle con-

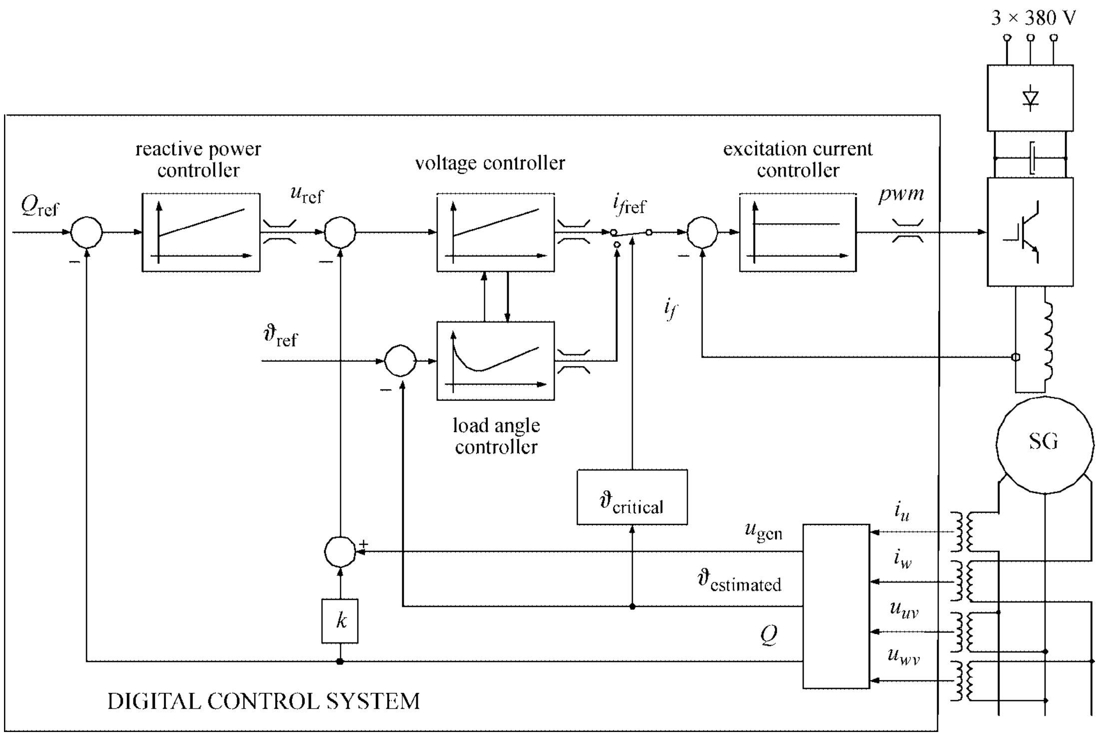


Fig. 2 Structure of excitation control system with load angle controller and estimator

troller is added (Figure 2). When load angle is near its unstable value ($\vartheta_{critical}$), the voltage controller is turned off and the load angle controller is turned on. In this situation, the load angle controller decreases the value of load angle (generator remains in synchronism) increasing the excitation current reference. So this control method enables stabile operation of a generator near the stability limit and expands the generator operating range. This method requires knowing of load angle instantaneous value. To avoid additional sensor, the value of load angle is estimated by measuring of two generator voltages and two generator currents.

Four-processor digital system is based on DSP ADMC300 processors. Communication between processors is achieved via synchronized serial bus. The communication rate is 4 MHz so twenty 16-bit words can be exchanged with the frequency of 3200 Hz. The real-time code is executed in an interrupt operating mode with the fixed frequency of 19200 Hz.

2 LOAD ANGLE MEASUREMENT

Load angle is measured using digital encoder that is connected to encoder input of digital signal processor. Processor internally convert digital signal from encoder to angle. Encoder angle is measured when one generator voltage crosses zero point. This angle directly corresponds to load angle of generator.

3 LOAD ANGLE ESTIMATION

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

From diagram on Figure 3 is obtained

$$\operatorname{tg}\vartheta = \frac{I \cdot X_q \cdot \cos\varphi - I \cdot R \cdot \sin\varphi}{U + I \cdot X_q \cdot \sin\varphi + I \cdot R \cdot \cos\varphi} \tag{1}$$

respectively

$$\vartheta = \operatorname{arctg}\frac{I \cdot X_q \cdot P - I \cdot R \cdot Q}{U \cdot S + I \cdot X_q \cdot Q + I \cdot R \cdot P}. \tag{2}$$

The value of a quadrature-axis synchronous reactance X_q and stator resistance R is needed for this estimation method.

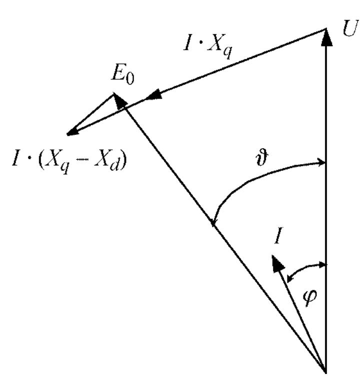


Fig. 3 Voltage-current vector diagram

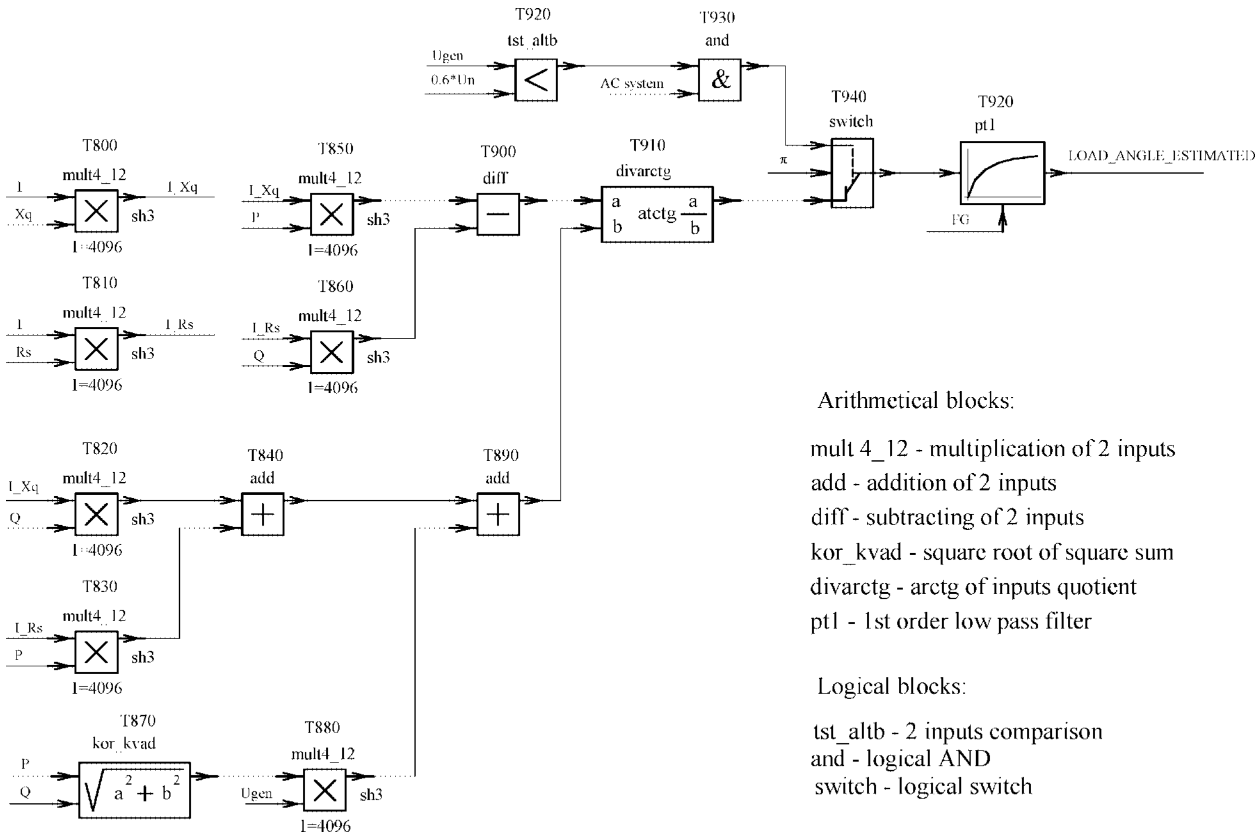


Fig. 4 Load angle estimation algorithm

The load angle estimation algorithm was implemented on the developed digital system DIRES 21 [2] (Figure 4). The algorithm was developed by graphical oriented software tool. In graphical environment, basic blocks implemented via assemble programming language, were connected in more complex control structure. Load angle estimation was realized by basic arithmetic blocks.

In situations when short circuit appears, generator voltage suddenly falls and generator current increases. Measuring equipment goes to saturation, and the measured results of active and reactive power are not reliable. The load angle estimated value is incorrect too. In such cases, the system forces the excitation current. The excitation current increases to its maximal allowable value determined by maximal excitation current limitation. When short circuit appears, the load angle estimator sets the maximal load angle value (180° el) and forces the excitation current increasing. This was realized by logical blocks *tst_altb* (T920), *and* (T930) and *switch* (T940) (Figure 4). So, if synchronous generator is connected to an AC system and generator voltage falls under 0.6 p.u., load angle estimator sets the maximal load angle value (180° el).

4 EXPERIMENTAL VERIFICATION OF LOAD ANGLE ESTIMATION METHOD

For the implementation of load angle estimation method and excitation control four-processor digital control system based on DSP ADMC300 [1] was developed. Software tool includes graphical interface for easier modeling of control algorithms was developed. For testing of algorithms software monitoring tool was also developed. It enables controller parameters optimizing as well as displaying and recording of testing results just via a PC. Experimental setup is presented on the Figure 5.

A. 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 Figure 6.

In the first experiment, reactive power of the generator is zero. In the second experiment the reactive power is inductive and is kept constant in the whole range of active power changing. In the

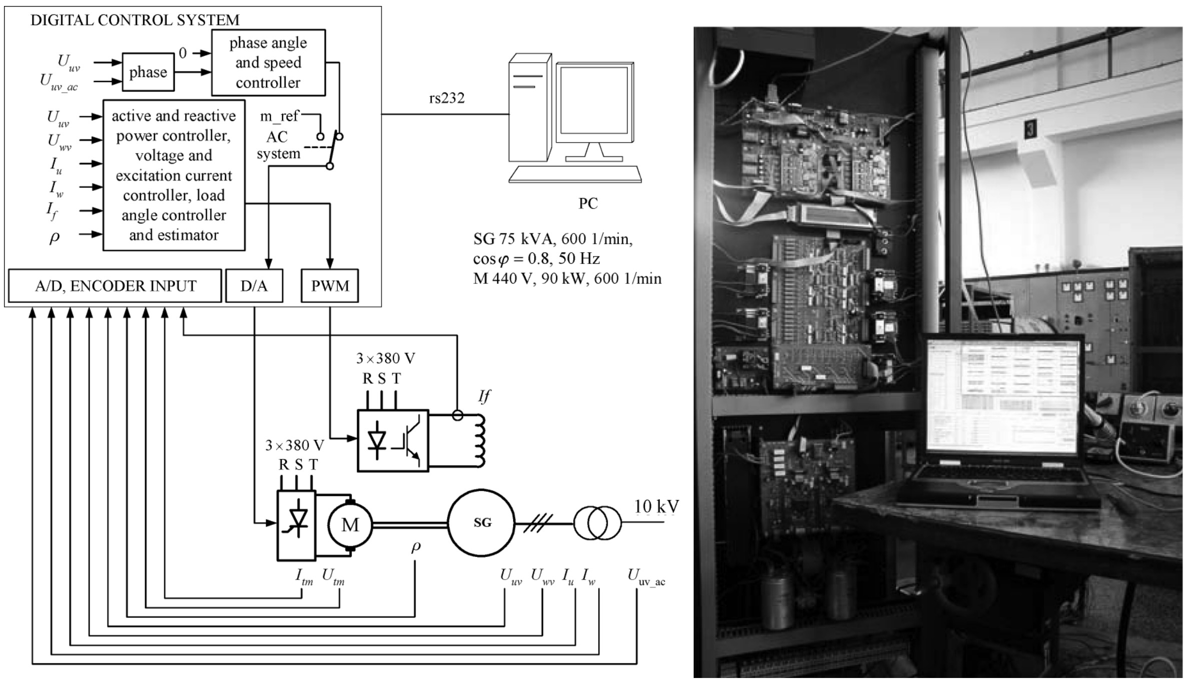


Fig. 5 Experimental setup

third experiment 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.

B. 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

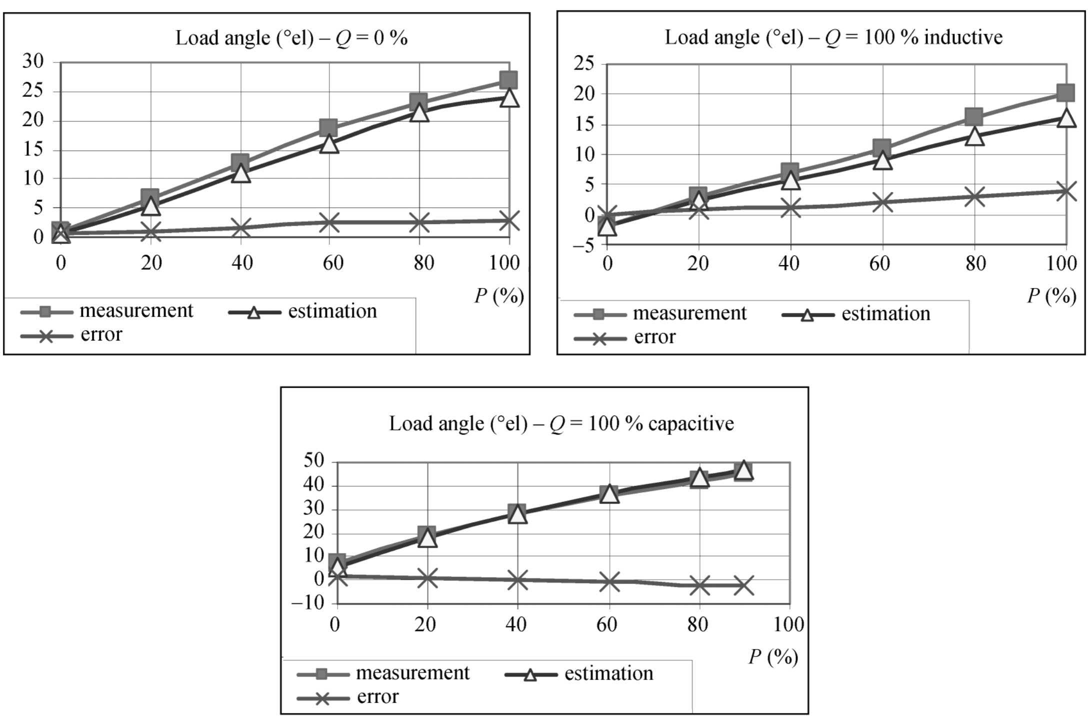


Figure 6 Measured and estimated load angle and estimation error with 0 % reactive power, 100 % capacitive reactive power and 100 % inductive reactive power during active power change from 0 % to 100 % of nominal power

moment $t = \sim 1$ s) from zero to 100 % of nominal power and again to zero after four seconds. The reactive power is kept constant via reactive power controller in all these experiments. In the first experiment (Figure 7), the reactive power is kept near zero. In the second experiment the generator is in inductive operating mode and reactive power is 100 % of nominal power. (Figure 8). In the third experiment generator is in capacitive operating mode and reactive power is 100 % of nominal power (Figure 9). In this three experiments reactive power controller is turned on. In fourth experiment generator is in capacitive operation mode, reactive power is 100 % of nominal power and reactive power controller is turned off. Synchronous generator loses synchronism (Figure 10).

First two experiments (Figures 10, 11) show good correspondence of estimated and measured results. The average estimation error in these experiments is less then 2,5° el. and maximal error during load angle increase is 10° el.

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 irrelevant. For algorithms that need to keep a generator in stabile operating mode, it is relevant operating range with load angles less then 90° el. So, if presented algorithm ensures stabile operating mode of a generator, load angle will never exceed 90° el.

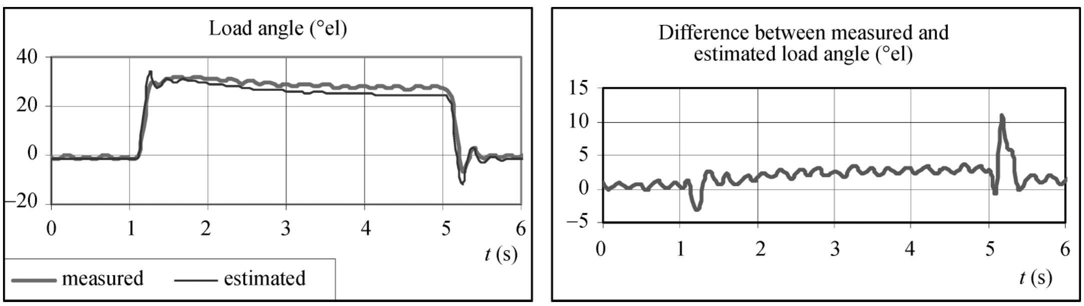


Fig. 7 The difference of measured and estimated load angle with zero reactive power during step change of active power with included reactive power controller

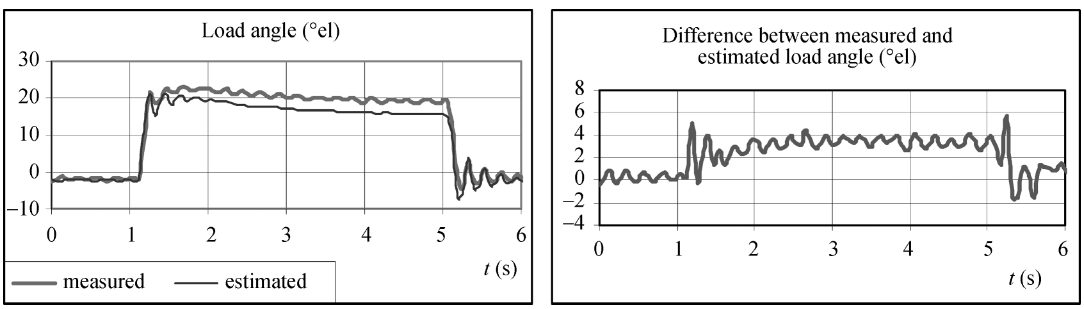


Fig. 8 The difference of measured and estimated load angle with 100 % inductive reactive power during step change of active power with included reactive power controller

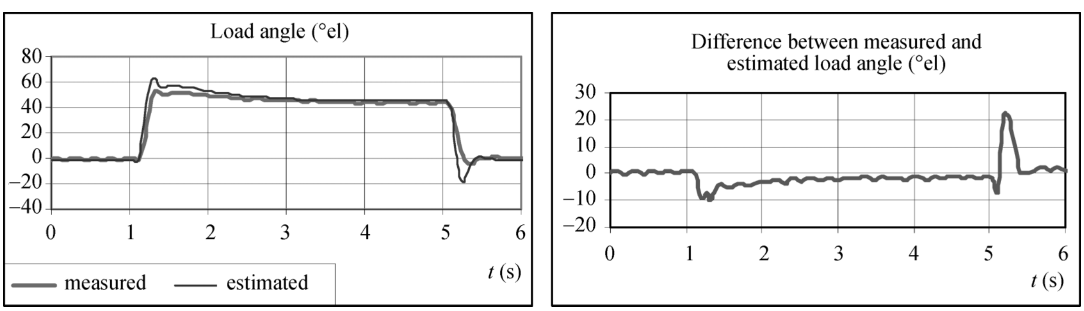


Fig. 9 The difference of measured and estimated load angle with 100 % capacitive reactive power during step change of active power with included reactive power controller

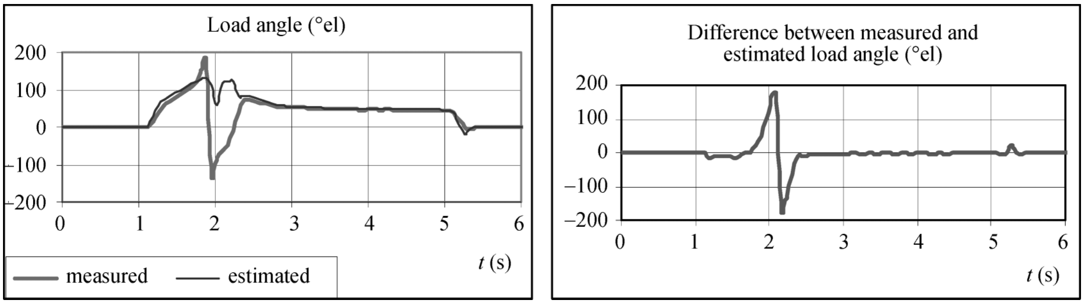


Fig. 10 The difference of measured and estimated load angle with 100 % capacitive reactive power and step change of active power with included voltage controller

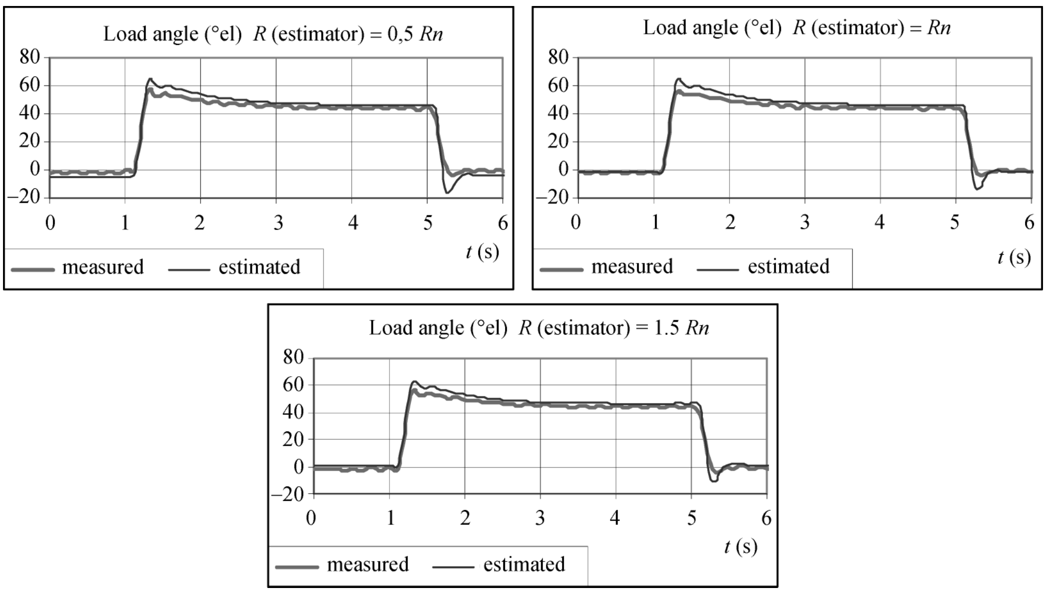


Fig. 11 The difference of measured and estimated load angle with different stator resistance R in load angle estimator

5 SENSITIVITY OF ESTIMATION METHOD DUE TO ERROR OF PARAMETERS OF ESTIMATOR

Parameters needed for the load angle estimation are quadrature-axis reactance X_q and stator resistance R. 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). There is active power step change (at the moment $t = \sim 1$ s) from zero to 100 % of nominal power and again to zero after four seconds. Stator resistance R and quadrature-axis reactance X_q in estimator are changed from 50 % to 150 % of nominal value with step of 50 %. Two different methods are used to determine sensitivity of estimation method to parameter change. First is mean absolute error (MAE) between measured load angle and estimated load angle. Second is static error (STAT). This error is defined as absolute error between measured and estimated load angle 3 seconds after step change of active power. In first set of experiments, value of stator resistance in estimator is changed (Figure 11). MAE and STAT criterions are shown in Figure 12.

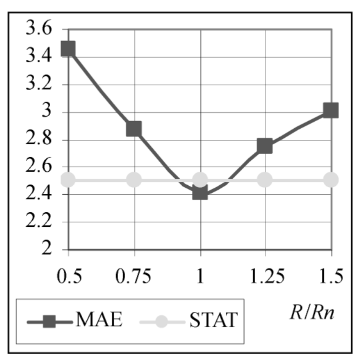


Fig. 12 MAE and STAT error of load angle estimation due to different stator resistance R in estimator

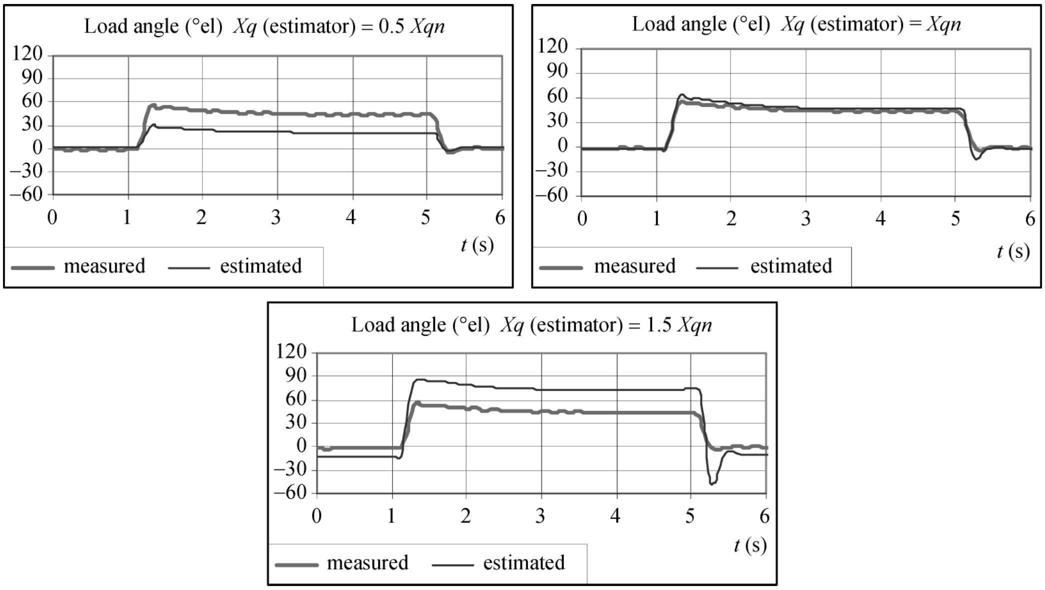


Fig. 13 The difference of measured and estimated load angle with different quadrature-axis reactance X_q in load angle estimator

In second set of experiment, value of quadrature-axis reactance in estimator is changed (Figure 13). MAE and STAT criterions for this set of experiments are shown in Figure 14.

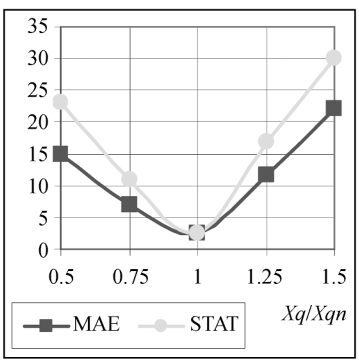


Fig. 14 MAE and STAT error of load angle estimation due to different quadrature-axis reactance X_q in estimator

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 hasn't a great influence on the accuracy of presented load angle estimation method. However, errors in determining reactance X_q influence on the accuracy of this load angle estimation method. The average dynamic absolute error significantly depends of quadrature-axis reactance X_q change.

6 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 and stator resistance R). Presented estimation method gives accurate enough results for load angles less then 90° el. Excitation control system with additional load angle controller improves the stability of a synchronous generator in capacitive operating mode. Future research will be based on further development of excitation control algorithms of a synchronous generator.

SYMBOLS

- ϑ – load angle of a synchronous generator
- R – stator resistance of synchronous generator
- X_d, X_q – reactances of a synchronous generator
- P – active 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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Mjerenje i estimacija kuta opterećenja sinkronog generatora. Tema članka je mjerenje i estimacija kuta opterećenja u sustavu upravljanja uzbudom sinkronog generatora. Kut opterećenja se mjeri digitalnim enkoderom, a estimacijska metoda je temeljena na parametrima sinkronog generatora i odgovarajućim odnosima u naponsko strujnom vektorskom dijagramu. Estimacijski rezultati uspoređeni su sa izmjerenim. Estimacijska metoda daje zadovoljavajuću točnost za kutove opterećenja manje od 120° el. Regulacija kuta opterećenja u sustavima uzbude povećava stabilnost sinkronog generatora u kapacitivnom području rada.

Ključne riječi: digitalni sustav upravljanja, sustav uzbude, estimacija kuta opterećenja, sinkroni generator

AUTHORS' ADDRESSES

Tomislav Idžotić, Ph.D.
Faculty of electrical engineering and computing
Department of electrical machines, drives and automation
Unska 3, 10000 Zagreb, Croatia
Tel./Fax: +(385 1) 6129-826/6129-705
tomislav.idzotic@fer.hr

Gorislav Erceg, Ph.D.
Faculty of electrical engineering and computing
Department of electrical machines, drives and automation
Unska 3, 10000 Zagreb, Croatia
Tel./Fax: +(385 1) 6129-876/6129-705
gorislav.erceg@fer.hr

Damir Sumina, M.sc.
Faculty of electrical engineering and computing
Department of electrical machines, drives and automation
Unska 3, 10000 Zagreb, Croatia
Tel./Fax: +(385 1) 6129-784/6129-705
damir.sumina@fer.hr

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