

Large turbogenerator's synchronous reactance's load dependence determined by measurements

Z. Maljković, I. Gašparac, M. Pavlica

Abstract – The paper presents research on underexcited turbogenerator operation capability. Measurements of basic electrical values for various loads have been carried out in case of 247 MVA turbogenerator. Synchronous reactance for various loads has been determined from measurements. Its influence on underexcited operation limits has been evaluated.

Index Terms—Turbogenerators, underexcited operation, end region, power system protection, power system measurements, power system stability

I. INTRODUCTION

TURBOGENERATOR'S power chart represents the diagram of reactive power versus active power of a generator, deduced from the synchronous machine's phasor diagram.

Standard power chart (PQ diagram) has its limits defined by: a) maximum field current in overexcitation quadrant, b) practical steady-state stability limit and minimum field current limit in the underexcitation quadrant, c) minimum active power limit and d) and maximum active power limit.

Usually, limit of underexcited operation is defined by steady-state stability limit and minimum field current limit. However, it has been noticed that some generators during continuous underexcited operation, even within the allowed operating area, have increased temperatures in the stator end region of the generator [1].

In Croatian network underexcited operation is often required in case of raised network voltage. Both electricity producers and Croatian transmission system operator are interested in precise knowledge of operating ability of every generator in the system [2].

Transmission system operator needs to know exact limits of underexcited operation ability in order to plan system reactive power supply, while electricity producers can earn additional income from the already existing generator property with no extra cost.

Therefore, methodology for determination of actual power chart, together with underexcited operation limits, has been defined and tested in case of 247 MVA turbogenerator (Fig. 1) [3], [4].

The generator has been equipped with measurement probes for measurement of magnetic flux density and temperature in active generator parts and especially in the stator end region. Load angle has been measured by optical encoder using the markings on the generator shaft. Relevant electrical load values (active and reactive power, voltage, current) have also been measured. All the data acquired by measurements are transferred to the central processing unit located in the power plant, which can be operated from

remote location (university laboratory), making remote on-line measurements possible at any given moment.



Fig. 1. Turbogenerator 247 MVA, 13.8 kV, $\cos\phi_n=0.85$, 3000 min^{-1}

Results of preliminary measurements and their effect on underexcited operation limit determination have been presented in this paper.

II. STANDARD TURBOGENERATOR POWER CHART

Synchronous generator's power chart [1] is a diagram that represents allowed steady state operation of a generator running at constant speed and connected to sinusoidal voltage of constant value. It is commonly used for general overview of generator's operation by power plant operating personnel and transmission system operator.

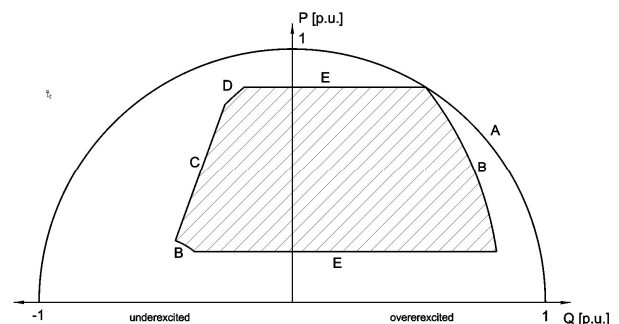


Fig. 2. Typical power chart of a turbogenerator

Fig. 2 presents typical power chart of a turbogenerator for rated voltage and rated frequency. The hatched area of the chart presents allowed steady state operation of a generator.

A. Stator heating limitation

The power chart boundaries are defined by limitations within the generator. The maximum armature winding

designed generator can continuously operate with maximum steady state armature current. For rated voltage,

this limitation in power chart becomes a circle whose upper half defines the generator limitations.

B. Rotor heating limitation

Typical turbogenerator's rotor carries the excitation winding. Usually, the limit is defined by maximum excitation current required for steady state operation within the scope of generator's voltage regulation. This current is directly related to maximum reactive power produced by a generator. In case of older generators with analogue excitation control system, the minimum excitation current is usually 10% of the rated excitation current. This limitation can be neglected altogether for new, digitally controlled excitation control systems.

C. Theoretical and practical steady-state stability limit

Steady-state stability is ability of the turbogenerator to stay in synchronous operation at slow load changes. Stability limit is maximum active power produced by a generator achieved by slow, steady change of load. Turbogenerator can, for given excitation, produce maximum active power at load angle equal to 90°el. This load angle defines the theoretical steady-state stability limit. However, the practical stability limit is usually defined by load angle of approximately 70°el.

D. Limits due to stator end region heating

Stator end region heating is caused by axial magnetic flux which enters the end laminations perpendicularly and induces eddy currents in the laminations. Overall limit of underexcited operation is usually determined by steady-state stability limits, but in some cases stator end region heating limits can be more stringent.

E. Turbine limitations

Upper limit on active power produced by turbogenerator is directly related to the limitations of the turbine connected to its shaft, minus the losses that occur during the transformation phase. The maximum active power produced by turbogenerator is at power factor equal to 1. It can be larger than the rated active power, if the turbine can supply the required active power. Turbogenerators with steam turbines have minimum power limit due to the minimum heat produced by a boiler.

III. LIMITS OF UNDEREXCITED OPERATION

Underexcited operation can be determined by three separate limits: minimum excitation, steady-state stability and stator end region heating.

A. Minimum excitation limit

This limit is nowadays rarely found, only in case of turbogenerator with older, analogue excitation control systems. Modern, digitally controlled excitation systems don't have this issue.

B. Steady-state stability limit

Mechanical torque produced by the turbine is converted by synchronous generator into electrical power, which can be computed by (1).

$$P = \frac{E \cdot U}{X_d} \cdot \sin \delta \quad [\text{p.u.}] \quad (1)$$

E - internally generated voltage (e.m.f.), p.u.

U - voltage, p.u.

X_d - synchronous reactance, p.u.

δ - load angle, °el.

Maximum power for given excitation is produced at load angle of 90°el. The theoretical limit in power chart is represented by perpendicular line at:

$$Q = \frac{U^2}{X_d} \quad [\text{p.u.}] \quad (2)$$

In order to avoid operating at the very edge of the stability limit, load angle of 70°el. is usually taken as a practical stability limit.

C. Stator end region heating limit

The stator end region heating limit is caused by localized heating of the generator's stator end region [5], [6].

This heating is caused by two components: main flux flowing in the radial direction and the end region leakage flux flowing in the axial direction.

Main magnetic flux flows parallel to laminations (B-H characteristic and specific losses of laminated material are given for this direction). The end region axial component of flux enters the laminations perpendicularly so laminations are less effective in suppressing the eddy currents caused by axial flux component. This causes the increased heating of end laminations. In case of underexcited operation, the two axial magnetic flux components, one coming from the rotor and other from armature winding, are supporting each other, the magnetic saturation of the stator teeth end laminations due to main flux is lower, so the resulting axial magnetic flux component is larger than in case of overexcited operation.

Assuming that the produced thermal energy is proportional to the square of the end region magnetic flux density and end region flux is proportional to the main air gap flux, the limit is defined as a circular segment with radius R and centre $(0, Q_c)$ (Fig. 3) [7], [8]. Its centre is determined by (3):

$$Q_c = K_1 \cdot \frac{U^2}{X_d} \quad [\text{p.u.}] \quad (3)$$

and its radius is determined by (4):

$$R = K_2 \cdot \frac{U}{X_d} \quad [\text{p.u.}] \quad (4)$$

Coefficients K_1 and K_2 can be computed by (5) and (6) respectively:

$$K_1 = \frac{N_f}{N_a - N_f} \quad (5)$$

$$K_2 = \sqrt{\frac{\Delta T}{K_t \cdot (N_a - N_f)^2}} \quad (6)$$

where:

N_a - number of stator winding turns

N_f - number of excitation winding turns

ΔT - temperature rise of the stator end region, K

K_t - thermal coefficient, K.

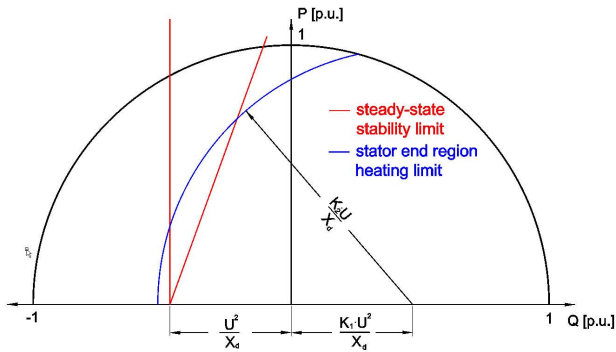


Fig. 3. Turbogenerator's underexcited operation limits

The number of stator and rotor winding turns are constant; maximum temperature rise is determined by the laminations' insulation thermal class, which is constant; and the thermal coefficient K_r , due to constant speed of the machine and unchanging surface for heat transfer, can also be considered as constant. Therefore, both limits that determine the maximum underexcited operation depend on generator voltage and synchronous reactance.

IV. PRACTICAL ISSUES

Experience has shown that the limit in underexcited operation of turbogenerator is often positioned more stringent than it might be.

Usually, the turbogenerator manufacturer provides generator's basic data, including the unsaturated synchronous reactance. This should by itself be sufficient to achieve certain margin from the theoretical limit.

The first one to set the limits are generator protection experts [9], who set their limits approximately 0.1 p.u. from the practical stability limit (Fig. 4).

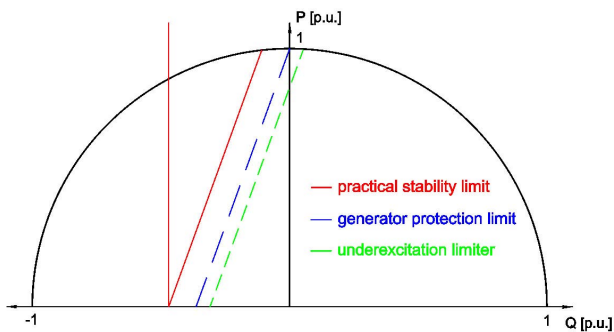


Fig. 4. Practical displacement of stability limit

Next, excitation control experts define the parameters of the underexcitation limiter, also taking some distance on the safe side from the limit defined for protection purposes. In the end, the underexcited operation can be severely narrowed.

The underexcitation limiter changes the limit with voltage change, but it doesn't take into account the change of synchronous reactance for given load.

In case of simultaneous occurrence of network voltage level and step-up transformer transformation ratio that would cause generator's underexcited operation with lowered voltage, which would cause decrease in magnetic saturation of the generator and increase of the synchronous

reactance. Since the lower synchronous reactance usually means larger and more expensive generator, it is reasonable to try to fully take advantage of this ability and define the underexcited limits more accurately. Information on synchronous reactance change with load, in case of particular existing turbogenerator, is necessary for determining the precise limits of its underexcited operation.

V. MEASUREMENTS

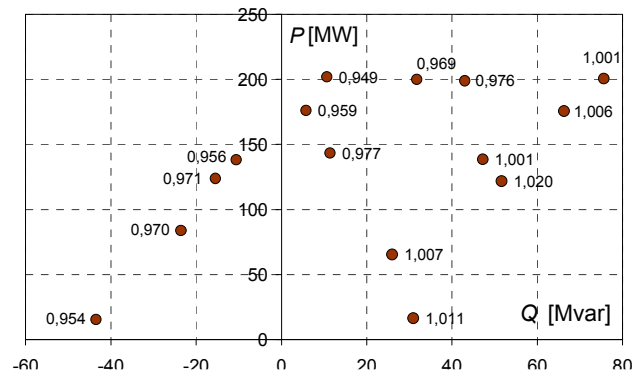
Measurements have been carried out in case of large turbogenerator operating in the Croatian electrical power system, with following rating: 247 MVA, 13.8 kV, $\cos\varphi_n=0.85$, 3000 min^{-1} .

Table I presents results of the measurements. Active and reactive power, voltage, armature current and load angle have been measured for various loads. Reference load angle has been measured for no-load operation and subsequent load angles have been determined in reference to it.

Turbogenerator loads have been manually set. Measurements have been carried out in various times of the day, in attempt to simulate the appropriate network conditions for particular load. This has been only partly successful, but the armature voltage for every measured load has been within the rated scope of voltage regulation ($\pm 7.5\%$) for the turbogenerator (Fig. 5).

TABLE I
MEASURED VALUES

| No. | P [MW] | Q [Mvar] | U [p.u.] | I [p.u.] | δ [°el.] |
|-----|--------|----------|----------|----------|-----------------|
| 1 | 15,5 | -43,5 | 0,954 | 0,196 | 12,27 |
| 2 | 16,4 | 30,9 | 1,011 | 0,140 | 5,61 |
| 3 | 65,4 | 26,0 | 1,007 | 0,283 | 21,96 |
| 4 | 83,8 | -23,6 | 0,970 | 0,363 | 40,52 |
| 5 | 123,9 | -15,5 | 0,971 | 0,521 | 48,76 |
| 6 | 121,9 | 51,6 | 1,020 | 0,526 | 32,35 |
| 7 | 143,5 | 11,4 | 0,977 | 0,596 | 46,15 |
| 8 | 138,6 | 47,2 | 1,001 | 0,592 | 37,47 |
| 9 | 138,4 | -10,6 | 0,956 | 0,588 | 51,01 |
| 10 | 175,7 | 66,3 | 1,006 | 0,755 | 39,92 |
| 11 | 176,2 | 5,8 | 0,959 | 0,744 | 53,79 |
| 12 | 200,1 | 31,7 | 0,969 | 0,847 | 51,33 |
| 13 | 200,6 | 75,6 | 1,001 | 0,867 | 42,89 |
| 14 | 199,0 | 43,0 | 0,976 | 0,844 | 48,80 |
| 15 | 202,1 | 10,7 | 0,949 | 0,863 | 56,66 |



Ability for underexcited operation is inversely related to

Based on phasor diagram (Fig. 6) of the turbogenerator,

direct axis synchronous reactance has been computed (7) for each of the load conditions. The difference between the direct and quadrature axis reactance is less than 3% and its influence on the load angle has been neglected.

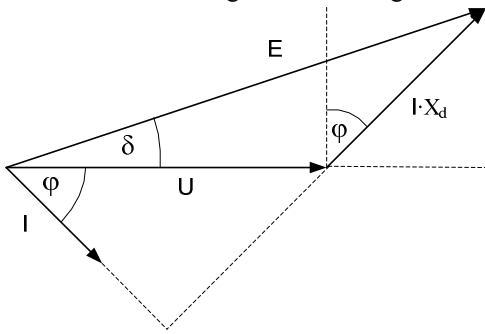


Fig. 6. Turbogenerator's simplified phasor diagram

$$X_d = \frac{U}{I} \cdot \frac{\tan \delta}{\cos \varphi - \sin \varphi \cdot \tan \delta} \text{ [p.u.]} \quad (7)$$

where:

I - armature current, p.u.
 $\cos \varphi$ - power factor.

Power factor can be determined by (8).

$$\cos \varphi = \frac{P}{\sqrt{P^2 + Q^2}} \quad (8)$$

Calculated values of synchronous reactance are given by table II.

TABLE II
CALCULATED VALUES

| No. | $\cos \varphi$ | X_d | U/X_d | U^2/X_d |
|-----|----------------|-------|---------|-----------|
| 1 | 0,335 | 1,961 | 0,486 | 0,464 |
| 2 | 0,468 | 1,860 | 0,544 | 0,550 |
| 3 | 0,929 | 1,839 | 0,548 | 0,552 |
| 4 | 0,963 | 1,911 | 0,508 | 0,493 |
| 5 | 0,992 | 1,877 | 0,517 | 0,502 |
| 6 | 0,921 | 1,824 | 0,559 | 0,570 |
| 7 | 0,997 | 1,867 | 0,524 | 0,512 |
| 8 | 0,947 | 1,855 | 0,540 | 0,541 |
| 9 | 0,997 | 1,842 | 0,519 | 0,496 |
| 10 | 0,936 | 1,741 | 0,578 | 0,582 |
| 11 | 0,999 | 1,844 | 0,520 | 0,499 |
| 12 | 0,988 | 1,804 | 0,537 | 0,520 |
| 13 | 0,936 | 1,763 | 0,568 | 0,568 |
| 14 | 0,977 | 1,793 | 0,544 | 0,531 |
| 15 | 0,999 | 1,821 | 0,521 | 0,495 |

Fig. 7 shows synchronous reactance relative to turbogenerator's reactive load.

Over the measured scope of reactive power (from 75.6 Mvar to -43.5 Mvar) synchronous reactance rises 12.7% (5% in underexcited part of the power chart), quotient U/X_d declines 15.9% (6.5% in underexcited part of the power chart) and quotient U^2/X_d declines 20.2% (8.3% in underexcited part of the power chart).

The results are expected, especially since the network voltage was not high enough for the generator voltage to be

of the synchronous reactance. The theoretical background of this phenomenon and its effect on generator's operation has been investigated [10]-[16].

Fig. 8 presents the ratio of voltage squared and synchronous reactance, which together with coefficient K_1 defines the position of both limits, as well as ratio of voltage and synchronous reactance, which together with coefficient K_2 defines the radius of stator end region heating limit.

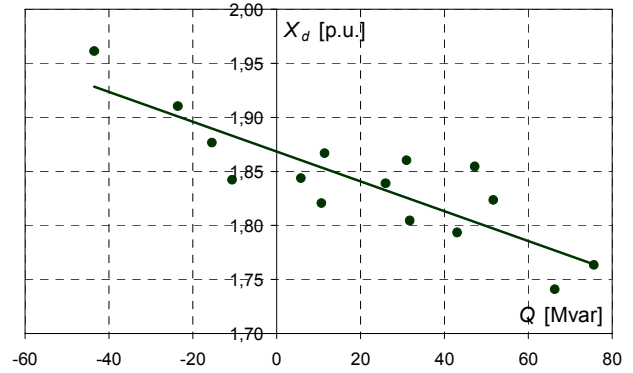


Fig. 7. Synchronous reactance X_d in relation to turbogenerator's reactive load

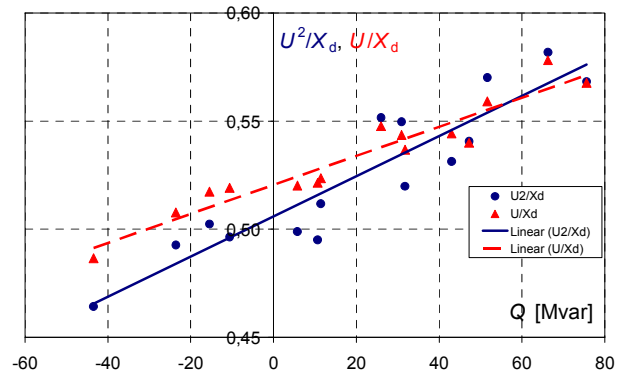


Fig. 8. Relation between U and X_d , for various loads

It can be concluded (Fig. 9) that the more reactive power turbogenerator absorbs, the stability limit moves to the right in the power chart and turbogenerator's ability to operate underexcited is diminished. For same load change stator end region heating limit, i.e. circular segment that represents it, has its centre displaced to the left in the power chart, but its radius is simultaneously decreasing. The rates of changes depend on terminal voltage and synchronous reactance.

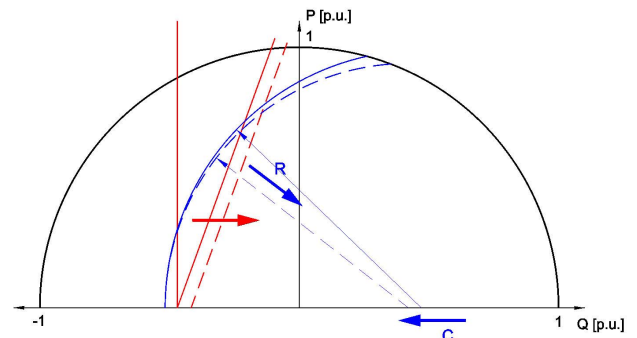


Fig. 9. Underexcitation limits displacement

lower terminal voltage have affected the saturation of the turbogenerator's active parts and caused additional increase

prevailing limit for the underexcited operation depends on coefficient K_t , which represents cooling conditions in the

stator end region. Its determination is pending due to difficulty to obtain necessary testing conditions. Magnetic steady state can be achieved relatively quickly, but in order to obtain thermal steady state conditions, the prolonged continuous operation for each load is required.

VI. CONCLUSION

This paper presents part of the research carried out in order to determine actual turbogenerator power chart. General, well known theoretical assumptions have been verified by measurements in case of existing 247 MVA turbogenerator. It has been shown that the synchronous reactance is sensitive to load conditions, which can affect generator's underexcited operation limits. The purpose of this paper is to provide experimental information primarily for protective relaying experts and excitation control experts.

It has been noticed in practice that too often the limits have been set according to manufacturer's data provided during the bidding process. Even when limits have been set by measured values, these are usually ones defined according to turbogenerator's unsaturated synchronous reactance values.

Regarding the future investigations into the matter, the Pt-1000 probes for stator end region temperature measurements, together with Hall probes for measurements of axial and radial flux density, have been installed. Since these measurements require prolonged operation with constant loads, approval and assistance of transmission system operator is vital. Once scheduled, with on-site help from plant personnel, these measurements should be simple to carry out by using the remote access to installed measurement system.

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VIII. BIOGRAPHIES

Zlatko Maljković was born in Vukovar, Croatia on February 11, 1951. He received B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from the University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia, in 1974, 1982 and 1990, respectively.

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Milutin Pavlica was born in Zagreb, Croatia in 1967. He received dipl. ing., M.Sc. and Ph.D. degrees in electrical engineering from the University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia.

His professional career started in TZV Zagreb, in 1993. He worked as a synchronous generator designer at Koncar Generators in Zagreb from 1994 to 1996. He worked as a teaching assistant and scientific researcher at Faculty of Electrical Engineering and Computing in Zagreb from 1996 to 2008. He is currently employed by Energy Institute Inc. from Zagreb, as a senior independent associate.