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Specifics and applicability of AC-drives technology usage in the static excitation systems of synchronous generators

G. Erceg, *Member, IEEE*, and R. Erceg, *Student Member, IEEE*

***Abstract*-- This paper points out specifics and applicability of the developed transistor (IGBT) converters' usage for AC-Drives in the synchronous generators' excitation systems. Basic characteristics of the control circuits in generators' excitation systems are shown. Static excitation systems with the transistor converters developed for AC-Drives have to be adapted. Hardware (input/output modules) has to be adapted considering the needs of the generator's static excitation. With the developed software package for AC-Drives new algorithms for control and voltage control of the generator are written. The transistor converters with mentioned adaptations can be successfully used in the excitation systems of the generators.**

***Index Terms*--Automatic Voltage Control, Static Excitation System, Transistor Converter.**

I. Introduction

Traditionally, DC exciters have been used in the excitation systems of synchronous generators, commonly together with the electro-mechanical voltage controllers. Lately, AC exciters with static diode rectifiers have been inducted into generators' excitation systems. Today, diodes are integrated into rotated parts (rotors) of the rotating exciters. Those systems are called brushless excitation systems.

Static excitation systems of the synchronous generators are mostly carried out with thyristor converters. They have considerably fast response compared with the excitation systems with rotating (DC or AC) exciters. New static excitation systems with thyristor converters are equipped with the digital voltage controllers based on developed DC drives technology.

Transistor converters with IGBT components are developed for AC-Drives, and are not used in static excitation systems. Their usage can be found in the brushless excitation systems. This paper points out applicability of transistor (IGBT) converters developed for AC-Drives with the digital control in a static excitation system of the generator.

G. Erceg is with Department of Electric Machines, Drives and Automation, Faculty of Elec. Eng. & Comp., University of Zagreb, Unska 3, HR-10000 Zagreb, Croatia (e-mail: gorislav.erceg@fer.hr).

R. Erceg is with the IT Division, Privredna Banka Zagreb, Ksaver 209, HR-10000 Zagreb, Croatia (e-mail: romina.erceg@pbz.hr).

II. Basic Characteristics of Generator's Excitation System

Generator's excitation system has to have three basic characteristics:

- a fast response,
- an isolated excitation system,
- a high drive safety.

Synchronous generators have to efficacy maintained the electric power system stability. In the cases of generator's inner defects an excitation system has to insure fast discharge. During the disconnection of the generator from an electric power network the excitation system has to efficacy limit the duration time of the generator's elevated voltage by forcing the excitation current decrease.

Faultless operation of the generator's excitation system is a reliability function of all embedded components and system integrity. Generator's excitation system components are usually over-dimensioned considering the electrical strains that can appear in the exploitation of the generator. Over-voltages in the exciter's circuit of the generator will occur in the following characteristic operating modes:

- drop out from the synchronism,
- fault synchronization,
- fast discharge.

Maximal values of the over voltages that can appear in excitation circuit during the above mentioned operating modes could be around $5 \cdot V_{fn}$ (V_{fn} - nominal excitation voltage). Because of that excitation systems have to be equipped with over voltage protection. Furthermore, over currents in the exciter's circuit will appear in the following working modes of the generator:

- short-circuit on the ends of the generator,
- fault synchronization,
- drop out from the synchronism,
- forcing the generator's excitation,
- short-circuit of the step-up transformer,
- oscillations with high amplitudes appearing in the excitation.

Selected static excitation has to have redundancy (considering the over current) and components' voltage characteristics that have 2.5 times higher voltage from the maximal voltage of the generator's exciter.

III. ADAPTATIONS OF THE AC-DRIVES

Today, transistor (IGBT) converters are widely used in AC-Drives with power up to 1.8MW (630V). IGBT modules of transistor converters in today's exploitation can be rated as very reliable components. The usage of the IGBT converters in AC-Drives' working modes shows high safety and reliability, particularly in the hard and demanding working conditions.

To use developed transistor converters in the static excitation systems of AC-Drives the adaptations in power supply circuits and particularly in the governing systems are needed. The adaptation of the power supply circuit is shown in Fig. 1. In the excitation system the transistor converter has to be adapted to work as two-quadrant chopper (1^{st} and 4^{th} quadrant). The generator's excitation current is controlled with the method of the pulse-width modulation via transistors V_1 and V_4. All the other transistors of the transistor converter are not controlled. In the DC link cause of the over voltage protection the transistor V_7 have to be embedded with an appropriate resistor. For bigger excitation currents instead of diode converter the half-controlled three-phase thyristor converter can be used. The transistor converter has to be chosen by taking into consideration the requests and specific working modes of the generator. A redundancy can be managed with two redundant transistor converters, each with their own control card or with one converter and two control cards.

During the hastily off loading (shutting down the generator from the electric power system or close short-circuits) considerable dynamic changes of the generator's voltage occur. Those voltage changes of the generator have to be taken into consideration when the power supply module of the control electronic is selected.

To use transistor converters (developed for AC-Drives) in the excitation systems of the synchronous generators we have to take into consideration the new supplemental functions. In the systems of automatic voltage control both voltage and current in three phases have to be measured,_considering the difference between active and reactive current components of the generator.

Monitor and protect functions developed with the software packages for the AC-Drive can be used as the same functions in the excitation systems of the generator. Logical control functions that are used in the excitation systems are included in the function blocks.

A part of hardware is common for the AC-Drive and the excitation system. Furthermore, the software package can be used for both applications. A part of the user software has to be modified or customized, for example give the permission to the customers to change: the software, indication of the alarm with the signal selection on the display, and other characteristic things for the excitation systems.

Complete governing and control algorithm for the excitation systems is different compared with the AC-Drives. The usage of developed software packages for the AC-Drives can obtain the requested governing and control algorithms for the excitation systems.

Another specific application request for excitation systems is the redundancy of energy circuit and/or control electronic of the transistor converter. This specific application is not characteristic for the AC-Drives. Therefore, because of the request for the redundancy the transistor converters that are used in the excitation systems have to have major adaptations in both hardware and software.

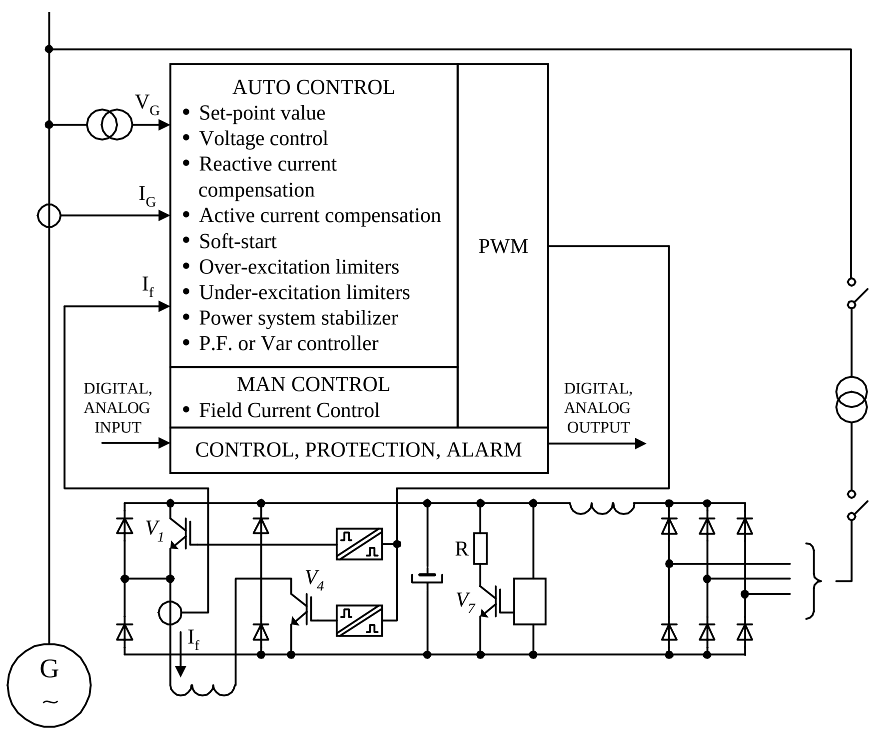

Fig.1 Structural diagram of the transistor converter adaptation (AC Drives) for the static excitation system of the generator

IV. Control Philosophy

Automatic voltage controllers in the excitation systems of the generators have two basic control modes: automatic (AUTO) and manual (MAN).

A. Auto Control Mode

Basic functions of generator's automatic voltage control are ensuring stabile state condition and stabile reactive power flow in electric power system. The actual voltage value of the generator is compared with voltage set-point value. The difference between these signals via voltage controller and transistor converter affects on the generator's excitation current. The effects of the control signal depend on the following functions that have to be included in the software for the automatic control of the generator (Fig. 2):

- voltage set-point value, it is the set value for the machine voltage,
- adjustable reactive current influence, it is a parameter for securing the parallel operating mode of the generator with the electric power system and/or with another generator,
- adjustable reactive current influence, it insure the voltage drop compensation on the resistive part or on the transformer that is connected on the generator,
- soft-start, it is gradual increase of the generators voltage and it prevent the generator's voltage surpass in the transient process of the excitation build-up,
- adjustable PID controller, it is used for the optimization of dynamic generator's characteristics. It ensures grand (high) precision in the steady-state condition and in acquiring dynamic generator's function.
- over-excitation limiters, they eliminate the generator's trip in the case of over-excitation. Over-excitation limiters are:
  a) V/Hz limiter to avoid over fluxing of the transformer that is connected to generator's clams,
  b) maximal exciter current limits the over-heating and ensures the ceiling for a short time. Limiter of the maximal exciter current can depend on the cooling media temperature.
  c) the stator's inductive current limiter. It can depend on the cooling media temperature.
- under-excitation limiters, they are used to avoid the trip of the generator during the under-excitation operation. The under-excitation limiters are:
  a) P/Q limiter with the correction of the limited characteristic dependable on the voltage,
  b) minimum field current limiter,
  c) limiter of the stator's capacitive current.

The power chart diagram of a salient pole generator (Fig. 2) shows the bounds of limiters effects in the both over and under excitation area of the generator.

- power system stabilizer, it improves the attenuation characteristics of the generator,
- P.F. or Var controller, which allows an operation of the generator to control the P.F. ($\cos\varphi$) or the reactive power.

B. Man Control and Follow-up

A Man Control is used for the periods of services and repairs, and also as a back up for Auto mode. In the case of the defect an Auto-channel automatically switches to Man-channel. In the Man Mode the excitation current control circuit has effects on the generator's excitation. To ensure a smooth changeover from the Auto to Man control and vice-versa the control system has to have an automatic follow-up algorithm. The non-active controller always follows up the active one.

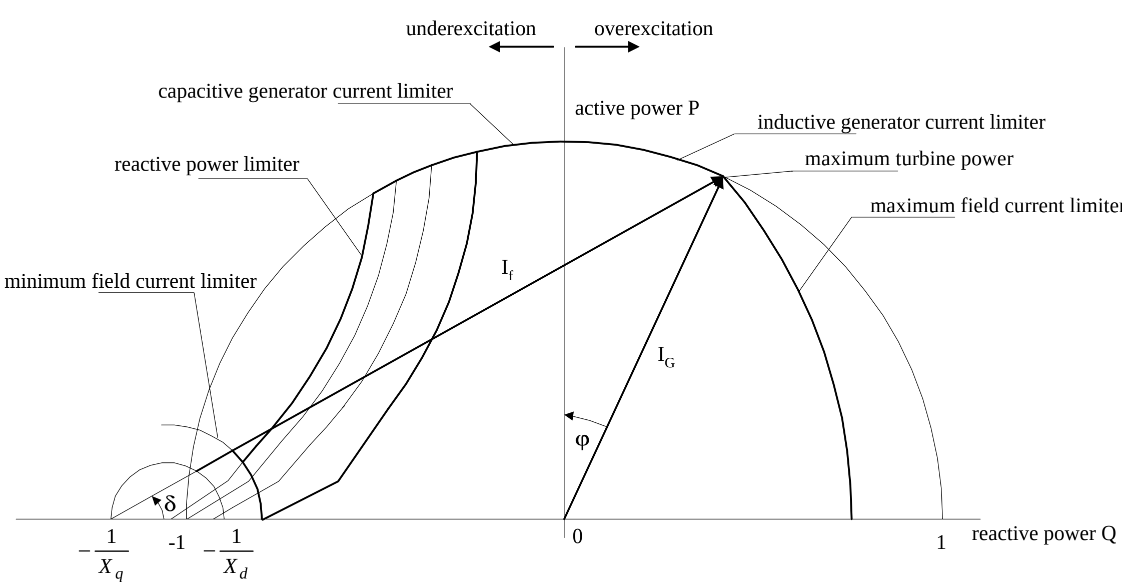

Fig. 2 Power chart diagram of a salient pole generator

In the case of dual automatic channel control of the generator's voltage the automatic follow-up is also necessary for the smooth changeover from the channel 1 to the channel 2 and vice-versa. Each of the channels is additionally equipped with automatic follow-up for the changeover on the manual mode.

V. DYNAMIC AND CHARACTERISTICS

Dynamic characteristics of static excitation system are specified with parameters of excitation system components, and with structure, algorithm and parameters of the automatic voltage controller. Transient excitation current characteristics of both static transistor and thyristor excitation systems are practically the same.

The voltage value of the transistor converter in the static excitation system does not have any influence on the transistor conducting pulse-width modulation. Conduction of the transistor is not dependable on the voltage power supply value of the transistor converter. In the static transistor excitation systems decreasing the excitation's voltage value of the generator (close short circuits) is slower considering the thyristor excitation. The energy of the condenser slows down the decreasing of the excitation voltage, and that has better effect on the generator's stability.

VI. COMPARING TRANSISTOR AND THYRISTOR CONVERTERS USED IN THE GENERATOR'S EXCITATION SYSTEM CIRCUIT

Simulation program package [6] is used to compare the work of transistor and thyristor converters. Simulation model is shown in Fig. 3a and 3b. Comparing results of power factor k_P, current distortion factor k_d, phase shift factor k_θ and harmonic distortion factor THD are given in Table 1., and comparing the load with the reactive power is shown in Fig. 4.

In the excitation systems the converter should have an output voltage 1.8-2.0 times higher than nominal. Therefore, till the generator overtakes the nominal load a thyristor converter assumption of reactive power is approximately 2 times bigger than with the transistor converter. Because of that the excitation transformer for thyristor converter have to have more power than for transistor converter. Current harmonic distortion factor THD is worse when the transistor converter is used.

Static excitation systems with thyristor converter have to be equipped with the switch and the resistor for the fast discharge, and with the over-voltage protection of the generator's excitation winding (anti-parallel connected thyristors). Transistor converter used in the generation's excitation loop does not need supplemental equipment for fast discharge and over-voltage protection of the generator's excitation loop. Equipment in the direct current inner-loop (condenser, transistor with the resistor) of the transistor converter executes the function of the over-voltage protection and fast discharge of the generator.

VII. CONCLUSION

Transistor (IGBT) converters are developed for AC-Drives. According to their characteristics (current, voltage, static, dynamic and exploitation) they can be successfully use for static and brushless excitation systems of the generators.

All the components of standard transistor converters for AC-Drive have to be chosen in the way to fulfill specific demands of the excitation systems.

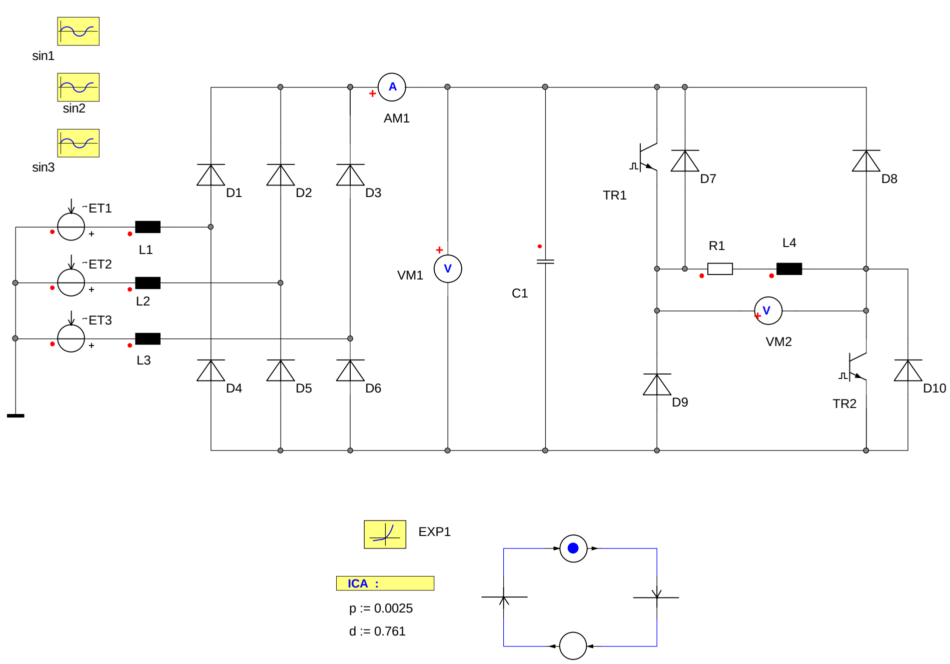

Fig. 3a Simulation model of transistor converter in the generator's excitation loop (R_1=11Ω; L_1=L_2=L_3=0.6mH; L_4=16.5H)

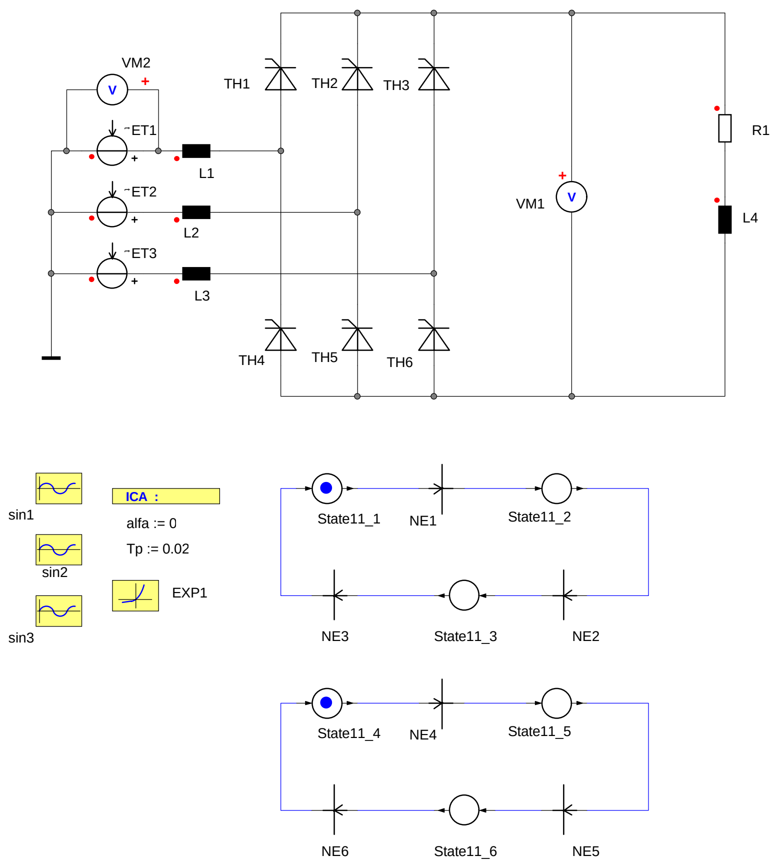

Fig. 3b Simulation model of thyristor converter in the generator's excitation loop (R_1=11Ω; L_1=L_2=L_3=0.6mH; L_4=16.5H)

TABLE I
COMPARING THE POWER FACTOR, DISTORTION FACTOR, PHASE SHIFT FACTOR AND HARMONIC DISTORTION FACTOR OF THE THYRISTOR AND TRANSISTOR CONVERTERS IN THE GENERATOR'S EXCITATION LOOP

	Transistor Converter		Thyristor Converter		
	$D=0.75$	$D=1$	$\alpha=60^\circ$	$\alpha=0^\circ$	$I_f\,[p.u.]=\frac{I_f\,[A]}{10\,[A]}$
I_f [p.u.]	1	2	1	2	D – duty ratio; α - firing angle
k_P	0.737	0.895	0.484	0.955	$k_P=\frac{P}{S}$
k_d	0.761	0.918	0.962	0.968	$k_d=\frac{I_{1rms}}{I_{rms}}$
k_θ	0.968	0.975	0.503	0.986	$k_\theta=\frac{k_P}{k_d}$
THD [%]	85	43	25	26	$THD=\frac{\sqrt{1-k_d^2}}{k_d}$

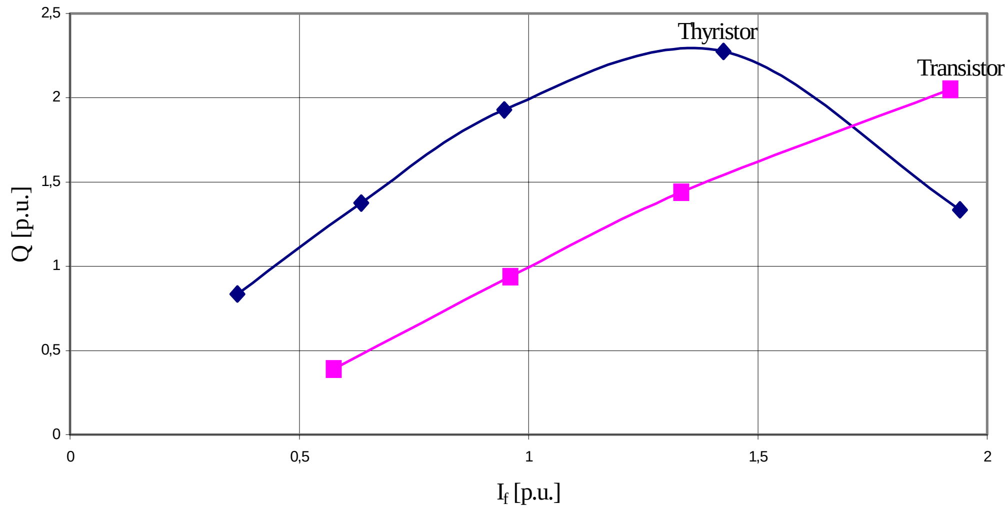

Fig. 4 Reactive power of transistor and thyristor converters

Input modules in a conducting system of the transistor converters have to be adjusted or new have to be realized according to standard measured modules for the excitation systems.

Control algorithms for excitation systems differ from the governing algorithm for the AC-Drives. For excitation systems a new software package have to be developed.

Developed transistor converters fulfill the drives safety demands of the generator's excitation system.

VIII. References

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IX. Biographies

Gorislav Erceg was born in Vrgorac, Croatia on January 15, 1942. He received his BSEE, MSEE and Ph.D. degrees from University of Zagreb, Faculty of Electrical Engineering and Computing in 1967, 1975 and 1996, respectively.

He joined dockyard Brodo-Split in Split, Croatia (1965) working in the Project Engineering Group. In 1966 at the Faculty of Electrical Engineering and Computing, Zagreb, Croatia he started as an assistant of Fundamentals of Electrical Engineering. Today as a head of the Department of Electric Machines, Drives and Automation and as an Assistant Professor he teaches undergraduate and graduate students.

Also, Mr. Erceg is a project leader of several industrial and government projects. He authored and coauthored numerous technical papers and studies in Control Engineering field, and is a member of IEEE Industrial Electronics Society, IEEE Power Society, KoREMA Society and Croatian Electric Engineering Society.

For his work presented in his Master's and Ph.D. thesis, numerous papers and studies he received three awards.

Romina Erceg was born in Zagreb, Croatia on August 26, 1971. She received her BSEE and MSEE degree from University of Zagreb, Faculty of Electrical Engineering and Computing in 1995 and 1998, respectively.

She was research assistant at the Faculty of Electrical Engineering and Computing (1995-2000) where she was involved with mathematical modeling and computer simulation of isolated electric power systems, and actual laboratory testing to verify the results.

She was a planning engineer with the Croatian Utility Company, and her responsibilities included distribution and sub-transmission system planning.

Currently she works as a project manager in the IT Division of Privredna Banka Zagreb d.d. where she leads group of engineers in the software development of the Bank.

Mrs. Erceg authored and coauthored 14 technical papers on Synchronous Generators, Excitation Systems and Voltage Controllers. She is a member of IEEE Industrial Electronics Society.