Panel Session Summary for the IEEE/PES 2001 WPM, Columbus, OH.
"Generator Overexcitation Capability", jointly sponsored by the Excitation System Subcommittee and the Power System Stability Controls Subcommittee.

Generator Over Excitation Capability and Excitation System Limiters

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Abstract – Sometimes, power system events have shown the need for generators to operate in the overexcited region to support stable operation. Operation up to, and transiently beyond, the overexcited limits from the capability curve is sometimes required. The two main issues in the paper are the generator capability in this region and the design of OEL (OverExcitation Limiters) in the excitation system that take full advantage of the capability allowed in the design and standards

Keywords – Synchronous Machines, Excitation Controls, Generator Controls, Protective Limiters, System Stability, Voltage Stability.

1. Introduction

To insure that generators are operated safely in the overexcited region during system events there are two key issues. One is the generator capability in both continuous and transient regions. The second issue is the protective limiters in the excitation system, that are designed to protect the generator.

During power system disturbances, some generators are called to support voltage by supplying vars, either at or transiently beyond the over excited capability. In section 2 of this paper the issues relating to generator capability are discussed. The top section of the capability curve relates to field heating, limiting field current to allowable levels. The second area on the capability curve to be considered in overexcitation situations is the stator current or MVA limit, on the right side of the curve. This is becoming more of an issue for units where the turbine may have been uprated and the generator has the original design. In this case the increase in generator MW output comes at the expense of available var output and overall MVA output capability.

Excitation limiters, specifically OEL and SCL (Stator Current Limit) functions are improving, and Sections 3 and 4 outline the historical perspective on these limit functions, and the approach taken in today's excitation controls. Done properly, the limits can insure more of the generator capability and design margins are available during system contingency events. Features such as recalibration of the limits based in inlet air temperature (air cooled machine), or hydrogen pressure for H2 cooled machines are available in today's excitation controls

2. Generator Overexcited Capability

The capability of the generator in the overexcited region is limited by the capability of cooling the field winding and the overall MVA output (stator current) of the machine. The overexcited region of the machine is also referred to as lagging power factor (in generator convention), where vars are being supplied from the machine. A plot of the generator capability curve is shown in Fig. 1. These curves show a machine whose capability follows ambient conditions, in this case the cooler inlet air temperature. The ISO rated nameplate is based on 40C inlet air temperature.

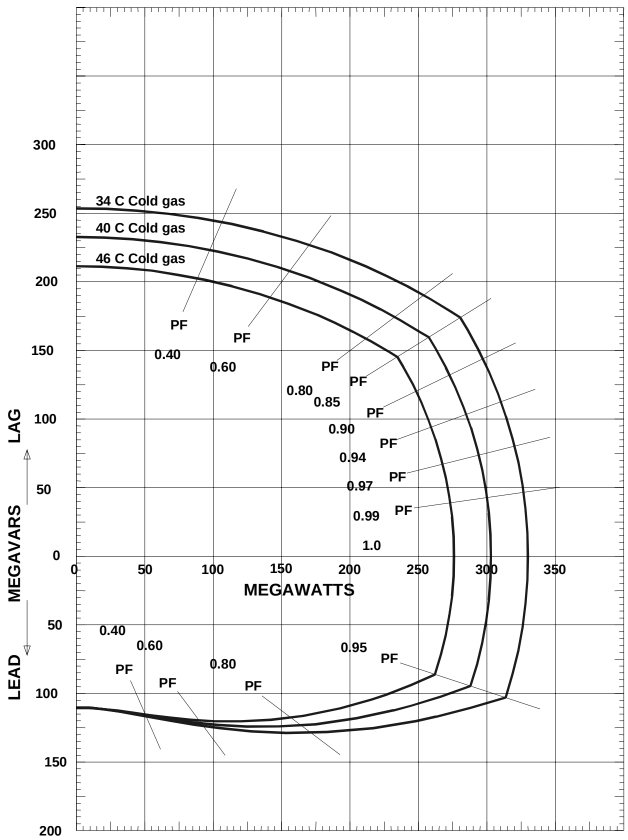

Fig.1 – Generator Reactive Capability Curve

The over excited region is the top part of the curves in Fig. 1, a locus of points from iteratively solving the load equation for a given value of P (MW) and finding the Q (MVAR) that results from a fixed field current. The field current is defined as IFFL, full load current at rated voltage, MVA, and pf. The field current limit is based on temperature profiles of the field in continuous operation. There are short time levels of overexcitation that are allowed by IEEE standards [1-2]. The basic premise of the standard is based on physical principles of thermodynamic heat balance, that is, higher levels are allowed for shorter periods of time, and lower levels for longer periods of time. The basic functional form can be fit with either an I*t or I^2*t inverse time curve. The curve corresponding to IEEE C50.13 is plotted in Fig. 2. The top curve corresponds to the values permitted by the standards. The remaining curves in Fig. 2 correspond to limiter functions in GE's present excitation systems, and will be discussed in later sections of this paper. C50.13 specifically relates to round rotor machines, and C50.12 that covers hydro-turbine generators does not give specific overexcitation guidelines. For this reason, C50.13 is used for hydro-turbine machine although its interpretation of the overexcitation allowable may be quite conservative. There may be an opportunity through studies and testing to allow increased overexcitation for

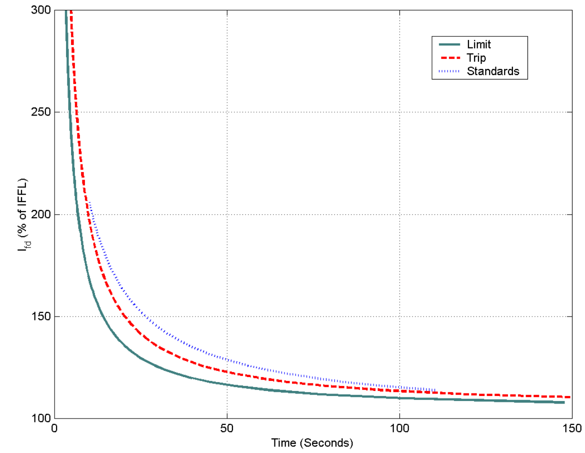

Fig. 2 – Overexcitation Capability and OEL Curves

hydro-turbine generators, and this may be important if they are a significant part of the generation mix. By way of example, Fig. 3 shows a comparison for a 55MVA 12 pole hydro-turbine generator between the C50.13 curve (lower curve) and an allowable overexcitation corresponding to an allowable 5C temperature rise in the field. The field time constant for this machine is about 20 minutes, substantially longer than the 1 minute seen on round rotor machines.

Some older round rotor machines may have larger margin over the standards level, it is not in general always the case.

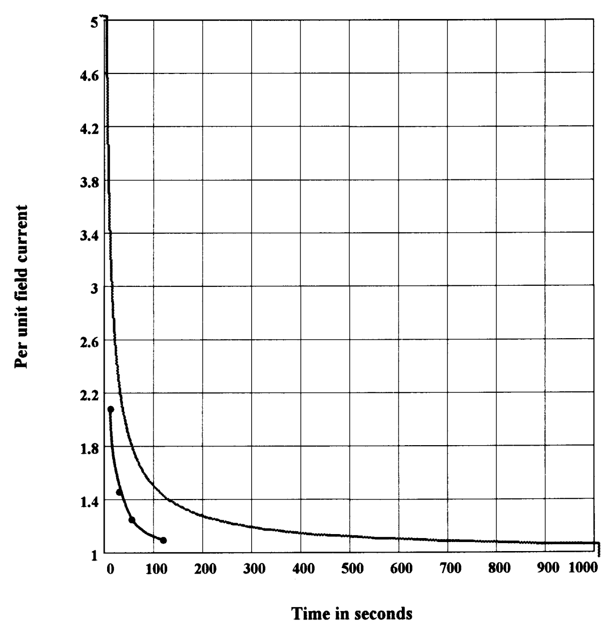

Fig. 3 – Over Excitation Capability for a Hydro-turbine Generator with a 5 degrees C Field Temperature Rise

Each machine has to be evaluated on a case by case basis to see what additional capability may be available. For any new machines the situation is much the same, but compounded now by the trend for increased flux density in the machines and consequent target of temperature profiles to match the allowable levels from standards curves. In this case there may be consistently less margin, but this again depends on the particular application. The proliferation of gas turbine driven machines with peak rating and ambient temperature following have to be taken into account in defining allowable levels and margins.

The other region of interest is the right part of the curve in Fig. 1 that represents a circle of constant MVA. This intersects the field-heating curve at the point where the generator (and turbine) has rated power and power factor output, commonly referred to as 'nameplate' conditions. Increasing the turbine by uprating, without a corresponding uprate of the generator, leaves an unprotected region at higher MW output if only an OEL excitation limiter is used. For this reason we will later describe both OEL and SCL limit functions which are in the GE EX2000 excitation system.

3. Excitation OEL limiter

To limit the excitation system from supplying excess field current, some form of overexcitation or maximum excitation limiter has been used. Some existing excitation equipment have a level detector on field current or voltage and a fixed timer that transfers to full load field in manual control, clearly not a good operating strategy for system voltage stability.

There are a number of ways the field current can exceed full load levels. The two most common would be during an overload when the system voltage is reduced, and transiently when there is a close in fault on the machine. Mitigating a system voltage reduction (collapse) scenario typically requires long time sustained field forcing. Transmission system faults, on the other hand, cause high fault currents and consequent high induced field current, which exist, only until the fault is cleared.

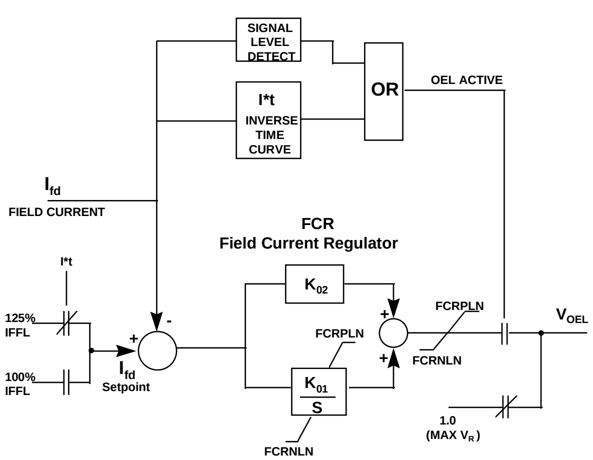

Fig. 4 - Over Excitation Limiter Block Diagram

A block diagram of the present GE design OEL limiter is given as Fig. 4. The OEL control is a takeover type function that replaces the AVR input to the firing circuits. When the OEL is not in control, its output is fixed at full level, which will insure the AVR signal will always be in control as it acts through a low value gate. When the OEL control is active, the primary control regulation function is a Field Current Regulator (FCR).

For close in faults where the induced field current is large, due to constant flux linkages in the generator with high stator current, the Signal Level Detector (SLD) will allow unlimited forcing for field current above 140% IFFL. This forcing can be sustained for a given period of time, usually at least 1 second but may be set to as high as 10 seconds for compound or brushless excitation systems. After the SLD has timed out the FCR is activated. The FCR is shown in the bottom of the figure as a proportional plus integral (PI) regulator. There are two reference values as input to the FCR, one at 125% times IFFL, and the second at 100% times IFFL. The FCR is a fast high bandwidth control that acts to reduce the field current to its setpoint. It should be noted that when the FCR is active the integrator in the AVR is disabled to prevent wind-up. For brushless excitation systems where the main generator field current is not accessible, a calculated value based on the alternator field current and time constant are used as an approximation.

The second way in which the OEL can be active is an accumulated I*t (I times t) calculation that provides an inverse time type curve. In the EX2000 system this is described as a **PR**otection **I**nverse **T**ime (PRIT) module. The PRIT calculation begins accumulating if the current is above 102% IFFL, but never reaches a trip point if the current is below 106% IFFL. This permits operation over the range of permissible generator voltages and tolerance in the field current calculation. The function of the calculation is to accumulate I*t through an integrator (a 60 seconds time constant is chosen to match the field thermal time constant) with a small feedback term (what is termed a leaky integrator). The leaky integrator permits an alarm to be generated at 102% of IFFL while not permitting a trip to occur until field current exceeds 106% of IFFL. If the PRIT module times out, then the field current regulator is activated with setpoint of 100% IFFL. There is additional logic, not shown in Fig. 3, which assures that the FCR remains in control if sustained over excitation were to occur (since the 100% IFFL level is below the 102% IFFL pickup). If the SLD circuit had already activated the FCR, then the setpoint

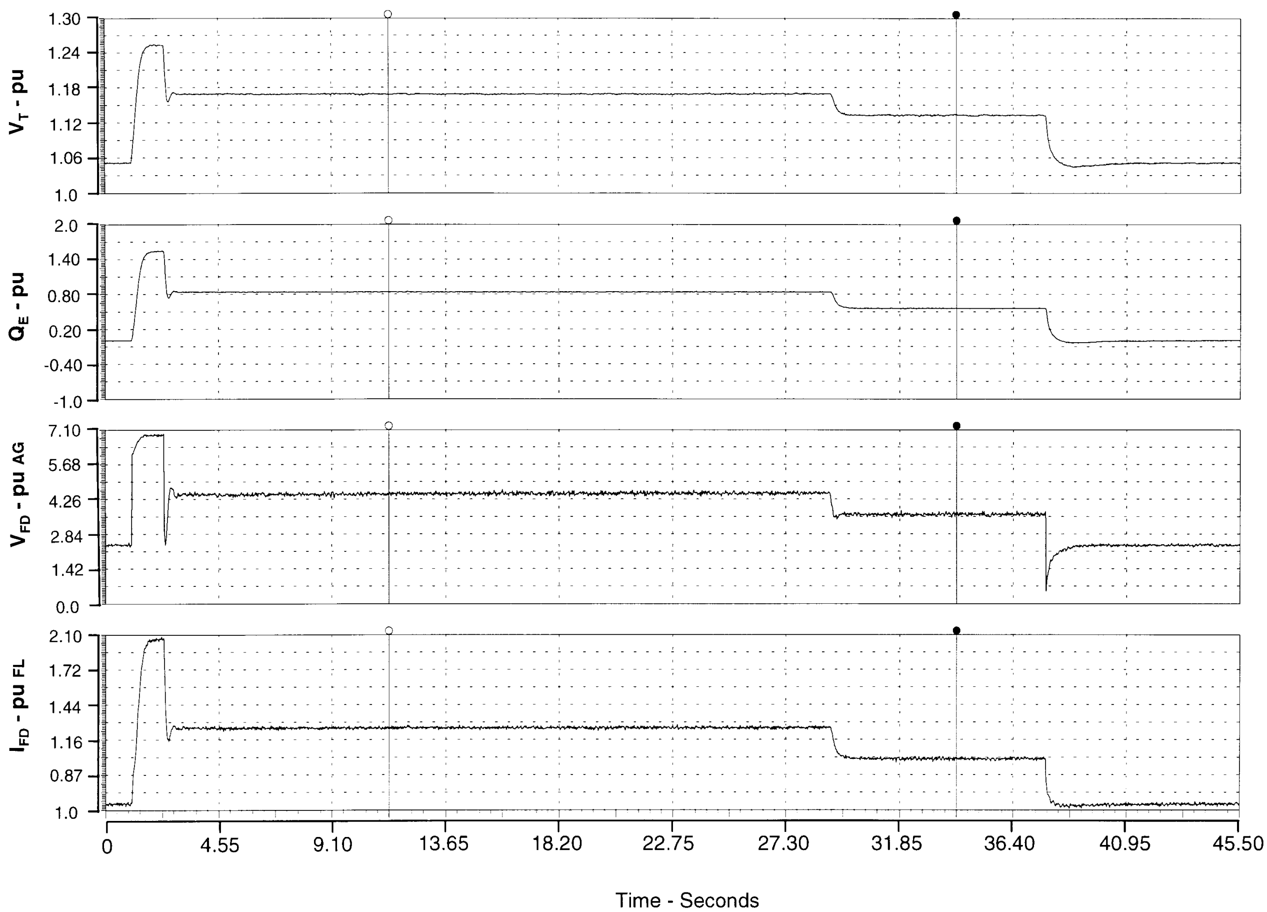

Figure 5 - Test of the OEL on a 250KVA Diesel-Turbine Generator in an Exciter Lab

will be reduced from 125% to 100% when the PRIT module times out.

Copies of the characteristic curve for the PRIT module, as typically set, are plotted in the lower two curves in Fig. 2. There are two curves given in the figure, one marked as trip level and the second marked as limit level. The accumulator on field current error in the PRIT module has actually three comparator circuits on the output. The highest level is for the trip output, a second level (typically 85%) for a transfer output (if there are two regulators and there is a transfer to a back-up regulator), and the lowest level for activation of the limiter. The limiter level is typically set to somewhere between 50 and 75% of the trip level. In Fig. 2, a level of 70% is shown to plot the limit curve. The design point for the PRIT curve is to have coincidence of the 120 second trip time at 112% IFFL per the IEEE C50.13 curve. For higher values of field currents the PRIT trip curve (and limit curve) are slightly within the requirements set forth in the IEEE Standards.

A plot of test results from a 250 kVA diesel driven generator in a controlled environment test lab is shown in Fig. 5. These plots show terminal voltage in per unit, generator var output in per unit, field voltage in per unit on air-gap base, and field current in per unit on full load base. For reference, the full load field current is 3.73 times the air-gap base for this generator. The OEL event was simulated by reducing the terminal voltage feedback to 0.8 pu while the generator was operating at full rated kW output and connected to the local utility. The sudden reduction in feedback signal causes the field voltage to reach ceiling level. Note, as described in the OEL model, full forcing is available for 1 second, then operation at 125% IFFL for a time determined by the inverse time curve in the OEL, followed by operation at 100% IFFL. After about 38 seconds the terminal voltage feedback signal is restored and the AVR resumes control, without a bump as the control prevents windup.

The OEL limiter, and the SCL limiter, has the capability of modifying its limits based on either hydrogen pressure (if the generator is hydrogen cooled) or inlet air temperature measurement. The set of capability curves in Fig. 1 illustrates

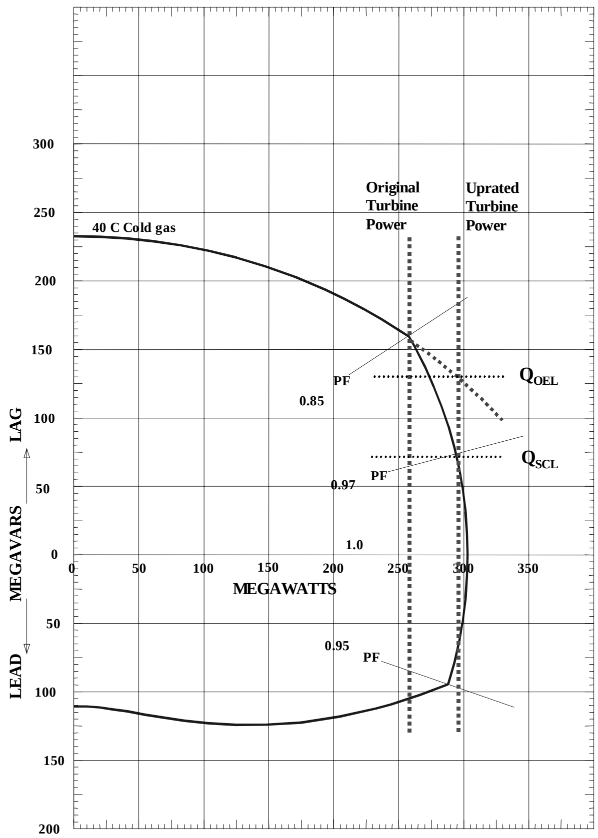

Fig 6 – SCL to Protect the Unit if the Turbine is Uprated

the need for this feature. Also, it should be mentioned that the OEL is monitoring both the heating and *cooling* of the generator field. After an OEL event, the integrator in the OEL is still active and it takes some time for it to decay to zero value. If a subsequent OEL event occurs before the machine had cooled to normal temperature, the time to accumulate to the limit value will be shorter to account for the fact the machine is hotter than normal. These are features that make controls smarter.

4. Excitation – Stator Current Limit

The generator stator current limit (SCL) is derived from the MVA limit, which results in a family of current limits as terminal voltage changes. This is shown in the right part of the curve in Fig. 6 as a circle with radius of rated MVA. The circle intersects the field-heating curve at the point where the machine has rated power and power factor output, commonly referred to as 'nameplate' conditions. The turbine power output is typically matched to this MW line, denoted as 'original' design turbine power on the curve. If, for example, a decision is made to uprate the turbine and not uprate the generator, then the MW line shown as 'uprated' could apply. In this case the limitation of MVA output (as reflected in (Q_{SCL}) is more restrictive than field heating (Q_{OEL}). For units operating with increased MW output, this leaves an unprotected region if only an OEL limiter is used.

The SCL control action depends on the operating point. In the overexcited region (+Q) the SCL needs to reduce excitation to bring the operating point down to the limit. In the underexcited region (-Q) the opposite is true, the excitation needs to be increased to bring the current/MVA to the limit. The other issue for the SCL is to insure that for faults on the transmission system, where the stator current is transiently high, the limiter action does not prevent forcing to ceiling for maximum synchronizing torque. This may require either a timer or slower acting control to ignore fast transient swings.

There are basically two ways to implement the SCL function. The present implementation of the SCL in GE equipment is as a *controller*, in much the same fashion as the var/pf control functions. The SCL controller provides inputs to the raise-lower contacts of the voltage setpoint, using the ramp function described ref. [14]. Inherently, this is a lower bandwidth control that has the benefit of not responding inappropriately to transient fault currents. If the var/pf control is active, it is taken out of service when the SCL is operating. The SCL can be re-calibrated as a function of hydrogen pressure or ambient temperature, in the same way the OEL and UEL

Another method would be to use a *regulator* that works on the MVA or stator current error, to drive it to the limit curve. In this case a PI control, similar to the FCR shown in Fig.4 could be used. A current or MVA error signal is used to develop an output in the proper sign to force the unit back to limit. An SCL regulator acts in a similar fashion to the underexcited limiter, UEL, as a signal input to the voltage regulator summing point.

5. Summary and Conclusions

The generator excitation is limited by the defined capability curve. In the overexcited region, the limiting factor is the design of the field circuit, a function of its cooling and thermal profile. In general, the design metrics are driven by the capability of the insulation systems, and structural aspects of elongation and winding stress. The guidelines for allowable overexcitation are those in C50.13. The design margins above C50.13 are a function of the specific machine design, and can be somewhat higher in hydro-turbine generators with salient pole laminated rotor structures. Studies and tests may allow increasing hydro-turbine generator over excited capability.

The generator capability is one half of the story, the remaining part is the limiters in the excitation system. Traditionally, limiters have been used as an automatic way of insuring the generator remains within its defined capability for either system events or operator action. Past limiter designs have been simplistic with fixed level and timers, and were not generally designed for maximum utilization of the capability region. Present designs, as shown, are much more flexible and can be tailored towards maximum utilization if the generator capability. This may be a reason to consider upgrading an older excitation system

6. References

[1] IEEE Standard C50.13 - 1989, “Requirements for Cylindrical Rotor Synchronous Generators.

[2] IEEE Standard C50.12 – 1982, “Requirements for Salient-pole Synchronous Generators and Generator/motors for Hydraulic-turbine Applications.

[3] “Recommended Models for Overexcitation Limiting Devices”, IEEE Task Force on Excitation Limiters, Trans. EC, Vol. 10, No. 4, December 1995, pps. 706-713

[4] A. Murdoch, R.W. Delmerico and S. Venkataraman, R.A. Lawson, J.E. Curran, and W.R. Pearson, “Excitation System Protective Limiters and Their Effect on Volt/var Control - Design, Computer Modeling, and Field Testing”, 1999 IEEE WPM Panel Session.

[5] M.M. Adibi and D.P. Milanicz, “Reactive Capability Limitation of Synchronous Machines”, IEEE Trans PWRS, Vol 9, No. 1, February 1994, pps. 29-40.

[6] N.E. Nilsson and J. Mercurio, “Synchronous Generator Capability Curve Testing and Evaluation”, IEEE Trans. PWRD, Vol. 9 , No. 1 , January 1994, pps. 414-424.

[7] W.R. Lachs and D. Sutanto, “Rotor Heating as an Indicator of System Voltage Stability”, IEEE Trans PWRS, Vol. 10, No. 1, February 1995, pps. 175-181

[8] W.R. Lachs, “System Reactive Power Limitations” , IEEE Conference Paper A79 015-9.

[9].A. Capasso and E. Mariani, “Influence of Generator Capability Curves Representation on System Voltage and Reactive Power Control Studies”, IEEE Trans PAS, Vol PAS-97, No. 4, July.Aug 1978, pps 1036-1041.

[10] A. Panvini and T.J. Yohn, “Field Assessment of Generators Reactive Capability”, IEEE Trans PAS, Vol. 10, No.1, February 1995, pps 288-296.

[11] J. Berdy, M. Crenshaw, M. Temoshok, “Protection of Large Steam Turbine Generators During Abnormal Operating Conditions”, CIGRE Paper 11-05, 1972.

[12] P.O. Bobo, J.W. Skooglund, and C.L. Wagner, “Performance of Excitation Systems Under Abnormal Conditions”, IEEE Trans. PAS, Vol PAS-87, No. 2, February 1968, pps 547-553.

[13] C.W. Taylor, “Optimizing Voltage Stability: Finding Effective Voltage Instability Countermeasures”, V. SEPOPE, May 19-24, 1996, Recife, Brazil.

[14] A. Murdoch, E.L. Owen, J.J. Sanchez-Gasca , M.J. D’Antonio, and R.A. Lawson, “Excitation Systems – The use of var/pf Control – A systems Stability Perspective”, 1998 IEEE SPM Panel Session.

Biographies

George E. Boukarim received his B.S., M.E. and Ph.D. in Electric Power Engineering, Rensselaer Polytechnic Institute in 1987, 1988, and 1998, respectively. Dr. Boukarim joined GE's Power Systems Energy Consulting (PSEC) in 1988 and rejoined in 1998, where he is currently Senior Engineer. Dr. Boukarim’s work has been in the areas of power system stability, generator controls and torsional dynamics. Other areas of interest are rotating machine transient studies, and the dynamic aggregation of large power systems and robust and optimal control.

Michael J. D’Antonio received his BSEE from Kansas State University in 1974 and his MSEE from Virginia Polytechnic Institute and State University (Virginia Tech) in 1982. He joined GE in 1975 and has worked in various technical and managerial positions and is presently Senior Application engineer for excitation system in GE's Industrial Systems business. Mr. D'Antonio has extensive experience in the design and application of microprocessor based controls system for power generation and has been issued 3 patents.

Brian E. Gott graduated from the University of Manchester College of Science and Technology with a Ph.D in electrical engineering in 1966. He joined the English Electric Company as a development engineer, working on both induction and synchronous machinery. He joined General Electric in 1968, as a development engineer in the electromagnetic area, and has held a wide variety of positions in both design and development engineering. He is currently Principal Engineer in Generator Technology for GE Power Systems business. Dr. Gott is a member of the IEEE PES Electric Machinery Committee, C50 Standards Committee, and a member of the U.S. Technical Advisory Group to IEC TC 2. on Electrical Machinery

Rodney A. Lawson received the BEE and MEE degrees from Univ. of Virginia in 1966 and 1973, respectively. He joined GE as Product engineer in 1966 and is presently Senior Application engineer in Industrial Systems. Mr. Lawson has extensive experience in the design, application and testing of excitation systems. He is a registered professional engineer in the State of Virginia, a member of the IEEE Excitation System Subcommittee, and has been issued 5 patents.

Alexander Murdoch received his BSEE from Worcester Polytechnic Institute in 1970, and his MSEE and Ph.D. from Purdue University in 1972 and 1975, respectively. Since 1975 Dr. Murdoch has worked for General Electric, in the Power Systems Energy Consulting, where he is a senior engineer. His areas of interest include rotating machine modeling, excitation system design and testing and advanced control theory. He is a member of the IEEE Excitation System Subcommittee.