Coordination of Overexcitation Limiter, Field Overcurrent Protection and Generator Control

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***Abstract*—The overexcitation limit of synchronous generator plays an important role in the voltage stability of power systems. Achieving maximum use of the overexcitation capability requires adequate coordination between generator control and protection. This paper provides an example of coordination between overexcitation limiter (OEL), field overcurrent protection and automatic voltage regulator (AVR) for a synchronous generator. The coordination achieved is then verified by a model simulation using an electromagnetic transient program for practical scenarios of interest. Suggested modifications to the ST1A type exciter model are presented to represent the complete functionality of the OEL function.**

***Index Terms*— Over excitation limiter (OEL), excitation controls, generator controls, synchronous machines.**

I. Introduction

THE operating requirements for synchronous generators are becoming more demanding in actual practice. One of these requirements is the use of the maximum reactive generating capability, which is mostly dictated by the rotor field winding thermal limit, also known as the overexcitation limit [1][2]. The impact of an appropriate use of this capability to maintain voltage stability in the power system has been widely recognized [3][4]. Appropriate use implies approaching the limit when necessary, but not going beyond and damaging the generator. The excitation control system, in particular the automatic voltage regulator (AVR) and the overexcitation limiter (OEL) are responsible for keeping the machine within its overexcitation limit [3][5][6][7]. The field overcurrent protection function is responsible to remove the machine from service in case control actions failed to maintain this limit [1][8]. Adequate coordination between these two, i.e. protection and control, is therefore critical [4].

In many cases coordination is studied based on parameters and characteristics of the machine and excitation controls in consideration. Practical tests to verify this coordination presents risk for the machine as well as for the power system [5][7]. In this paper, we discuss the coordination between OEL, AVR and protection, but also verify the performance for certain important conditions where they are required to properly coordinate. The performance is verified by simulation, thus the accuracy of the models used is very important. These coordination studies are possible now unlike in the past because detailed models for OEL, AVR and other excitation control systems are available in the literature [3][5][6][9][10]. This paper is organized as follows:

In Section II we briefly describe the concepts of generator capability curve, short time overload capability of the rotor, and emphasize the importance of maximizing the use of this capability for the power system.

In Section III we explain the typical interaction between AVR, OEL and field overcurrent protection. Also we describe concepts such as field forcing, instantaneous and inverse time OEL, protection as well as coordination between them.

In Section IV we use as an example, the type ST1A exciter [9], and discuss suggested modifications to provide complete OEL functionality. We used the work done by Murdoch [5][11] as an initial framework and introduced enhancements as described next. In his work, Murdoch used a signal level detector (SLD) to implement the field forcing logic, but no details were provided on this SLD element. In our work, an integrating timer is used to perform the field forcing time measurement due to the oscillating nature of the rotor field current I_{FD} during severe disturbances. After the field forcing interval, an instantaneous OEL limit of 160% of rated was used instead of the 140% and 125% levels used by Murdoch. The field current regulator (FCR) we used was of the proportional type, while Murdoch used a proportional integral type. The output of the FCR we used was a summing type of OEL, instead of the takeover approach used by Murdoch. The measurement of the inverse time used in our work is identical to that presented by Murdoch.

In Section V an example system is modeled using the alternative electromagnetic transients program (ATP/EMTP) with the suggested modifications. Two cases are considered: (1) a close in fault, and (2) a temporary overload with voltage reduction. The various conditions of interest, such as field

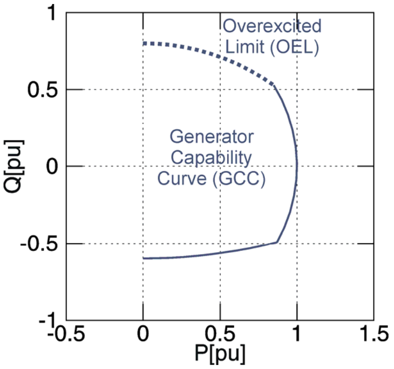

Fig. 1 Synchronous generator capability curve

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forcing, instantaneous OEL, inverse time OEL action, effect of ceiling voltage, as well as the transition to normal are observed and discussed.

II. OVEREXCITED CAPABILITY

The operating limits of a synchronous generator are defined by the generator capability curve (GCC) that is plotted in the P-Q plane, as shown in Fig. 1. The upper portion of the GCC curve in Fig. 1 is the overexcited limit, and restricts the amount of reactive power that the machine can supply to the power system. For the power system, it is important to obtain the maximum reactive power support available from the generator to ensure an adequate level of voltage stability in the system. Therefore, a proper coordination between protection and controls associated with this limit is required, to maximize the utilization of a given machine.

The overexcited limit in the GCC curve is defined by the current carrying capability of the rotor field winding. The limit curve plotted in Fig. 1 is a steady state limit, and corresponds to the rated current of the rotor field winding. The rotor winding is also capable of overloading for short time periods with an overload characteristic similar to that defined by the IEEE/ANSI Standard C50.13, as shown in Fig. 2 [2]. This overload capability helps to provide additional reactive power support to the power system during disturbance events. The two most common disturbance events are: the overload with a reduced system voltage, and the faults close to the generator. In this type of events the overexcited limit acts as a dynamic limit, because the maximum rotor current allowed is function of time.

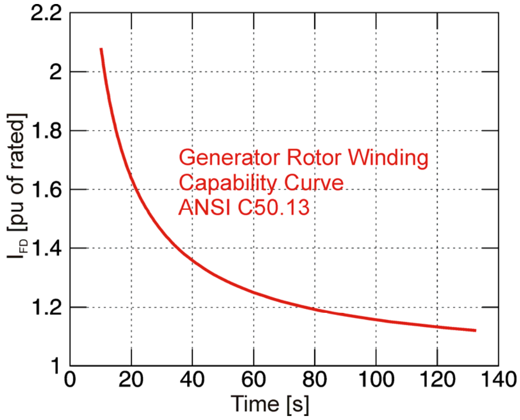

Fig. 2 Field current short time overload curve from C50.13 Standard.

III. EXCITATION CONTROL, LIMITS AND PROTECTION IN THE OVEREXCITED REGION

The main function of the excitation system is the control of generator terminal voltage with the help of the automatic voltage regulator (AVR). When the operating point of the machine in the P-Q plane moves beyond the overexcitation limit, the overexcitation limiter (OEL) is activated and is responsible to bring the operating point back inside the GCC curve. In this process, the OEL function and the main exciter make use of the short term overload capability of the rotor field winding as required by the particular event. Only in the case that these two control functions are unsuccessful to bring the machine within its capability, the field overcurrent protection operates and trips the generator out of service. The OEL function recognizes several conditions during an overexcitation disturbance even, as described next.

Field Forcing : At the start of a disturbance, i.e. a fault for instance, the AVR is allowed to execute control with no limits and apply the required field voltage and current to the rotor winding. These values may be very high, i.e. in the range of 10 pu for the voltage and 2.8 pu for the current. The field forcing is only allowed for a short time in the range of 100 ms to 1 s. This time is typically enough for the backup protections in the power system to operate in case of a fault.

Field Current Limit Instantaneous : If after the field forcing interval the field current exceeds the current limit pickup, i.e. the maximum field current allowed before reaching the short time overload curve, then the field current regulator is activated to bring the field current within the current limit pickup. The current limit pickup is in the range of 160% of the rated field current.

Field Current Limit Inverse Time : In case that the field current does not exceed the current limit pickup, the short time overload curve is used. Once the field current and duration time reach this curve, the field current regulator is activated and the current limit pickup is reset to a lower value, in the order of 100% of the rated field current. In this way, the field current is restored back to rated values.

Field Overcurrent Protection : The protection should allow the full use of the short term overload capability of the rotor winding. Thus the time-current characteristic of this protection is located above the field current limit inverse time characteristic but below the short term overload capability of the rotor. In many modern OEL designs, before the field overcurrent protection is allowed to trip (knowing that previous control actions were unsuccessful), the backup excitation system takes over control to restore the field current within the rotor winding capability.

IV. MODELING OF EXCITATION CONTROL, OVEREXCITATION LIMITER AND PROTECTION

An example system with a potential source controlled rectifier exciter is used to illustrate the overexcitation coordination concepts. The model ST1A defined in IEEE 421.5 standard is recommended to represent this type of system, and is shown in Fig.3. In the ST1A model, the overexcitation limiter (refer to Section 9 of IEEE 421.5 standard) may be applied in two places: (1) at the summing point from the output of the block with gain K_{LR}, or (2) at the low level gate from the V_{OEL} signal. In this work, we use the summing point approach and include some modifications to the existing limiter represented by the gain K_{LR} and the signals I_{LR} and I_{FD} associated with that path.

The field current limiter already included in the ST1A model is a summing type that represents basically the field current limit instantaneous control action. In the ST1A model, the field forcing action is represented by zeroing the K_{LR} gain at the start of the disturbance for the desired amount of time.

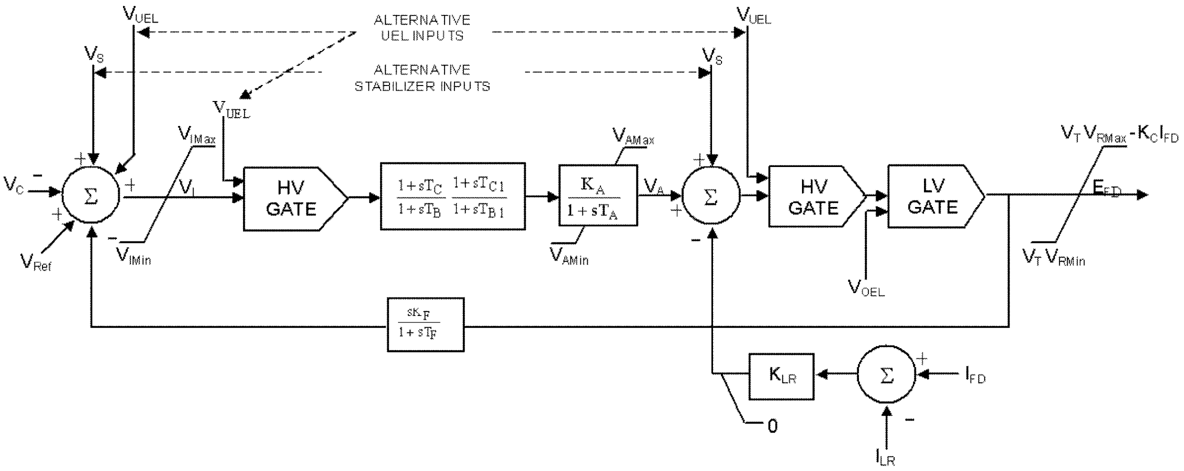

Fig. 3 Type ST1A exciter model – Potential Source – Controlled Rectified Exciter

The field current limit inverse time is not represented in the ST1A model. Also the dynamic behavior of the current limit pickup as function of the inverse time limit is not mentioned in this model.

The OEL used in this example is shown in Fig. 4, and uses the work done by Murdoch [5] as the basis. The OEL described here replaces the K_{LR}, I_{FD} and I_{LR} path of Fig.3. In Fig. 4 the field forcing is achieved by delaying the logic output from the corresponding block for the desired amount of time. During the field forcing interval the OEL signal follows the normally closed path at the right side of Fig. 4 producing a zero output level. The measure of time during field forcing is achieved using a “leaky” integrator, as shown in Fig. 5. The integrator accumulates the output of a comparator with a pickup current I_{PKPI} of 160% of the rated I_{FD}, i.e. it is an integrating timer. The use of an integrating timer is advantageous due to the oscillating nature of the current I_{FD} during severe disturbances. In these disturbances, the I_{FD} value may oscillate above and below the I_{PKPI} value with a time period shorter than the desired field forcing time. The advantage is that the integrating type of timer adds all the short time periods if they are close in time with each other. In Fig. 5, the following parameters were used: $K_{LKI} = 0.25$, $T_I = 1$, $C_{LVLI} = 0.194$ to obtain 200 ms of field forcing action.

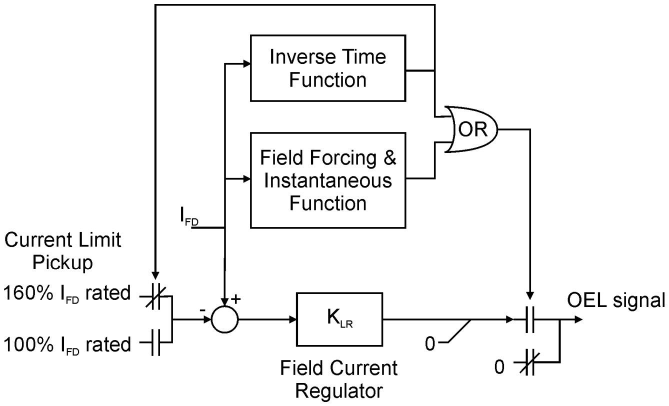

Fig. 4. Overexcitation limiter block diagram

The field current limit instantaneous is activated in Fig. 4 after the field forcing interval by allowing the signal output

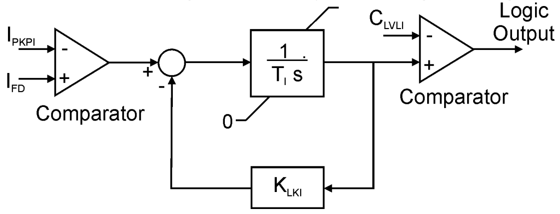

Fig. 5. Field forcing and instantaneous function

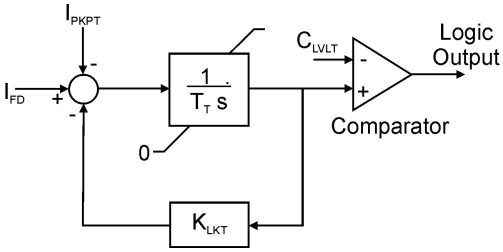

Fig. 6. Inverse time function

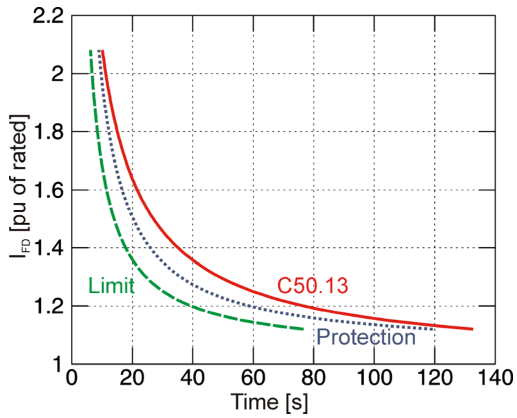

Fig. 7. Coordination of OEL limiter, field overcurrent protection and generator overexcited capability.

from the K_{LR} block to become the OEL signal output. Once activated, the field current regulator produces a signal proportional to the amount of overexcitation. During the field current limit instantaneous interval the current limit pickup remains at 160% of the rated I_{FD} current.

The field current limit is also activated in Fig. 4 by the inverse time function. Once activated, the inverse time function modifies the value of the current limit pickup from 160% to 100%. This change causes the I_{FD} current to return quickly within the rated value range. The measure of time is achieved in Fig. 6 using a "leaky" integrator so that the operating time is inversely proportional to the I_{FD} current value in excess of the I_{PKPT} level. To approximate the short time overload characteristic of Fig.2, the following parameters are used in this example: $K_{LKT} = 0.255$, $T_T = 60$, $C_{LVLT} = 0.156$, I_{PKPT} = 102% of the rated I_{FD}. The value of C_{LVLT} just given corresponds to the field overcurrent protection tripping level. The field current inverse time limit needs to use a lower value in the range of 70% of the protection level, i.e. $C_{LVLT} = 0.109$. The resulting coordination in time vs current of the approach just described is shown in Fig.7.

V. RESPONSE OF EXAMPLE MODEL OF EXCITATION CONTROL, OVEREXCITATION LIMITER AND PROTECTION

The model described in Section IV is implemented here using the alternative electromagnetic transient program ATP/EMTP. The sample system is a 360 MVA, 18 kV round rotor generator connected to an infinite bus through a 0.055 pu impedance. Two important cases are studied in this section: (1) close in fault, and (2) overload with voltage reduction.

A. Close in Fault

The initial conditions of the generator used for the test are V_T=1.0 pu, P_0=0.77 pu, Q_0=0.47 pu, $I_{FD} = E_{FD}$ = 0.8886 pu of rated. A double phase to ground BCG (i.e. B and C phases to ground) short circuit fault is applied at 400 ms from the start of the simulation. The instantaneous currents at the generator terminals reach about 15 pu as shown in Fig.8. The fault in Fig. 8 is cleared around 700 ms and a stable power swing is observed following this. The voltages in phases B and C drop down below 30% of rated during the fault, as shown in Fig.9. The phase A voltage also drops down to 60%. Fig. 10 shows that the rotor field current I_{FD} increases above the 160% current limit pickup value, and oscillates as previously noted in Section IV. After the fault is cleared, the current I_{FD} in Fig. 10 shows a stable swing following the swing of currents of Fig. 8. The excitation field voltage E_{FD} shown in Fig. 11 initially tries to increase by the action of the AVR. However, the voltage drop during the fault causes the ceiling voltage E_{FDMAX} to limit this action. In Fig.11, the instantaneous field current limiting action is observed in the E_{FD} signal around 200 ms after the fault started. Fig.12 shows the output of the OEL limiter (labeled as FCL), indicating the field forcing

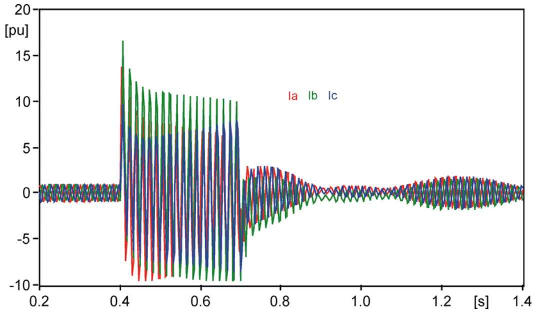

Fig. 8. Generator currents for a BCG close in fault.

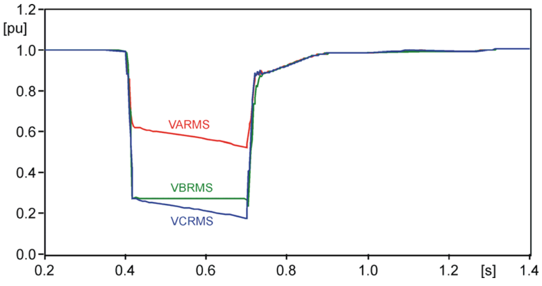

Fig. 9. Generator terminal phase voltages in rms for a BCG close in fault.

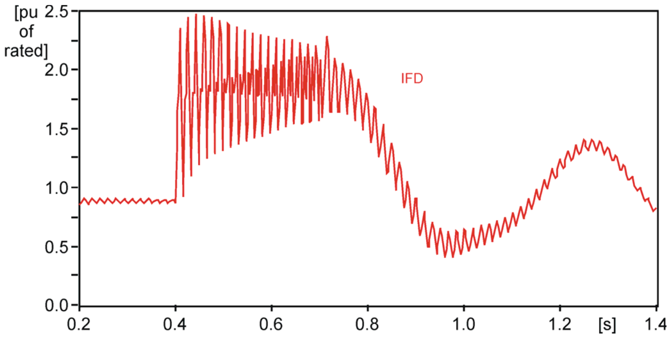

Fig. 10. Generator rotor field current for a BCG close in fault.

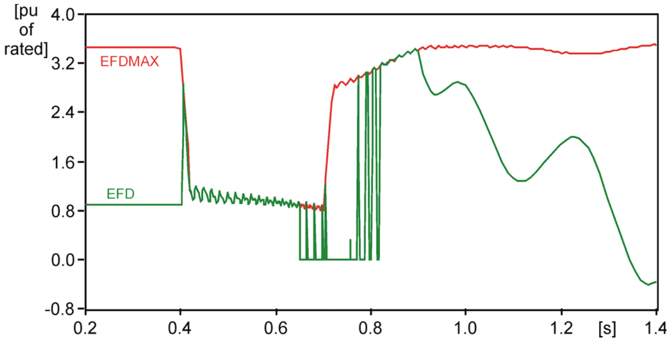

Fig. 11. Generator rotor field voltage for a BCG close in fault.

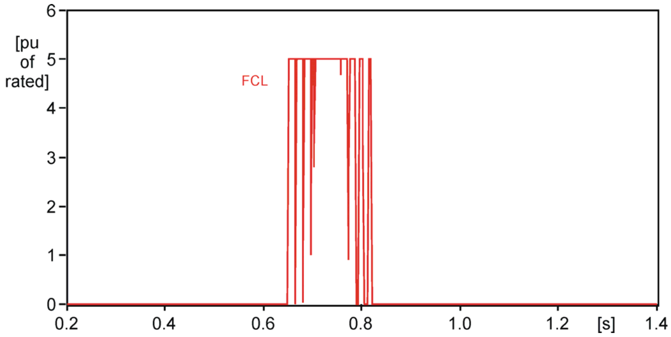

Fig. 12. Rotor field current limiter (OEL signal) for a BCG close in fault.

duration of 200 ms, with limiting action starting only after that interval. It can be noticed that the limiting action stops when the I_{FD} current drops below the 160% current limit pickup level around 800 ms in the time scale.

B. Temporary Overload with Voltage Reduction

The initial conditions used in this test are the same as those used for the close in fault. The initial rotor field current I_{FD} is close to the rated value, therefore an additional reactive demand to the generator is expected to take it into the overload condition. The overload with voltage reduction is produced in this example by connecting a large inductive load at the generator terminals, i.e. an inductive impedance of 0.11 pu. Fig. 13 shows that the generator terminal voltage drops down to 70% of rated after the overload is applied at 400 ms. The voltage again drops down but only slightly at about 12.1 s. The voltage recovers back to normal after the overload condition is removed at 25 s time. The rotor field current I_{FD} shown in Fig. 14 initially increases and oscillates around the 160% level and then stabilizes at this level within 1.0 s from the start of the overload at 400 ms. In Fig. 15, the excitation field voltage E_{FD} increases by action of the AVR when the terminal voltage drops, but it is limited by the reduced ceiling voltage E_{FDMAX}. Also in Fig. 15, it can be noticed that field forcing action is available for about 400 ms instead of the expected 200 ms. The reason for this additional field forcing duration is because the field current I_{FD} oscillates around the current limit pickup 160% value, and the integrating timer of Fig. 5 only accumulates the 200 ms by adding the small periods of time in which the I_{FD} current is above the current limit pickup value. After the field forcing interval, the instantaneous OEL limiter starts to act at about 800 ms as indicated by the E_{FD} signal in Fig. 15. Fig. 16 gives an overall view of the rotor field current I_{FD} behavior during this test. The instantaneous OEL limiter takes control immediately after the overload condition is applied following the field forcing interval, and regulates the I_{FD} current to the 1.60 pu of rated. Once the inverse time OEL limiter operates at approximately 12.1 s, the field current I_{FD} is regulated down to rated value. The time of 12.1 s is in accordance with the control limit curve of Fig. 7 for the 1.60 pu of rated I_{FD} value. In Fig. 17, we

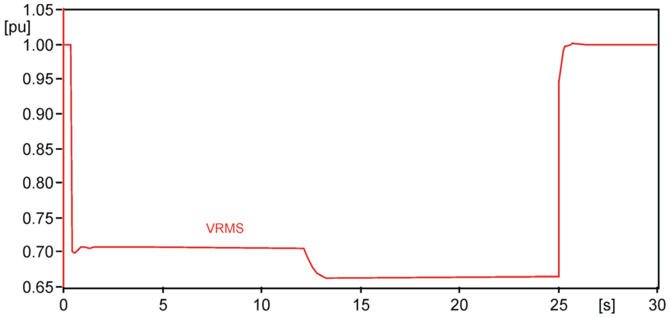

Fig. 13. Generator terminal voltage in rms for the overload test.

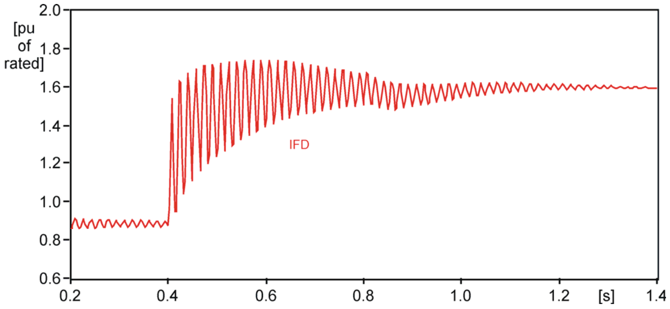

Fig. 14. Generator rotor field current for the overload test – initial part.

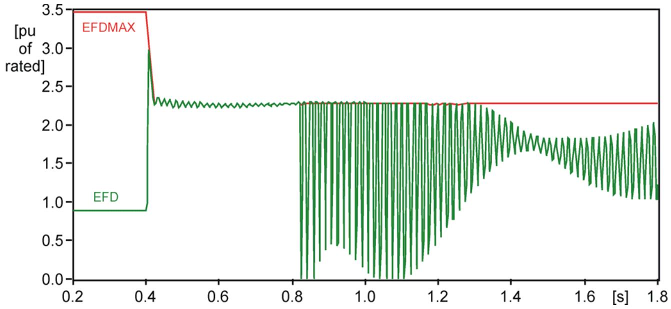

Fig. 15. Generator rotor field voltage for the overload test – initial part.

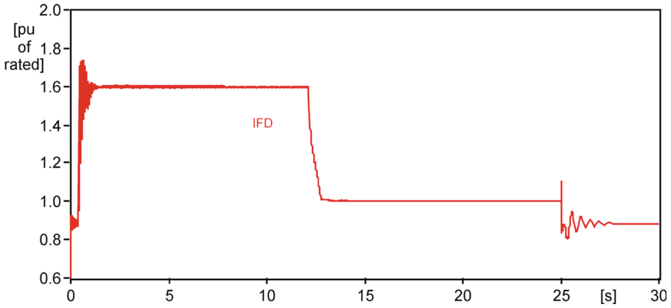

Fig. 16. Generator rotor field current for the overload test – overall view.

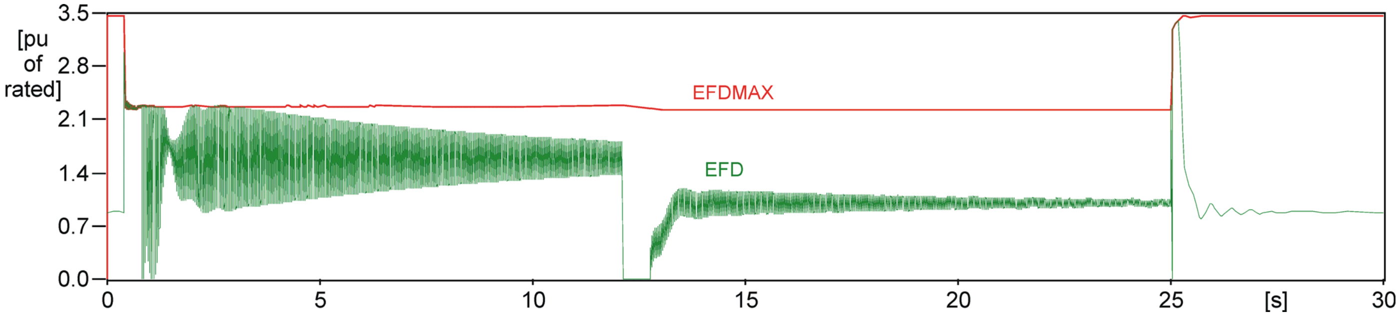

Fig. 17. Generator rotor field voltage for the overload test – overall view.

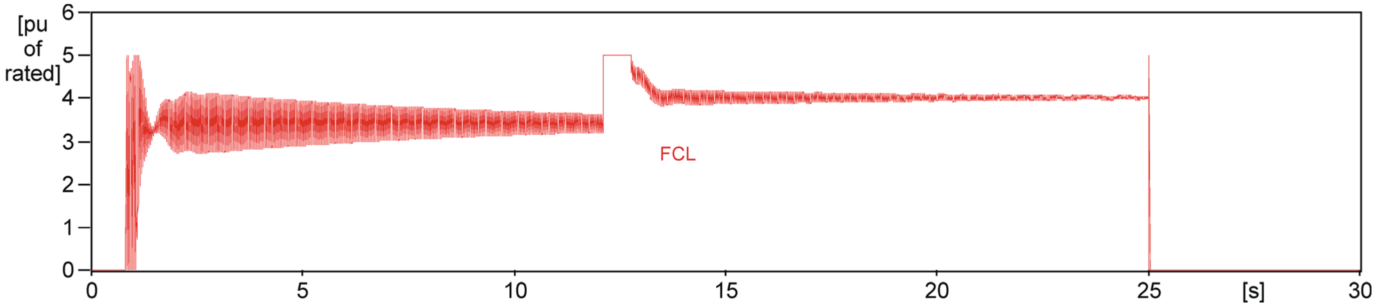

Fig. 18. Rotor field current limiter for the overload test – overall view.

notice that the ceiling voltage E_{FDMAX} is only limiting the exciting voltage E_{FD} until about 4 s in the time scale. The voltage E_{FD} is reduced at the time of 12.1 s by the effect of the OEL inverse time limiter in accordance with the field current I_{FD} behavior of Fig. 16. Finally, in Fig. 18 the field current limiter OEL signal (labeled FCL), is active until the time of 25 s returning then the control back to the AVR.

VI. SUGGESTED MODIFICATIONS TO ST1A MODEL

The paper has proposed modifications to the ST1A model to enhance the OEL functionality during overexcited conditions. The modifications were described in detail in Section IV of the paper and a summary of these proposed modifications are given below:

1. A field forcing duration time measure was introduced using an integrating timer. This type of timer is advantageous because it can take into account the short time periods in which the current I_{FD} oscillates above the pickup value, I_{PKPI}.
2. An inverse time current characteristic was added to the model so that it coordinates with IEEE Standard C50.13 [2]. This characteristic ensures that the OEL limiter, the protection and the machine capability coordinate for the entire range of operating conditions of the machine.
3. A dynamic field current limit pickup which is dependent on the inverse time function was added. This dynamic limit helps in providing full overload capability during the instantaneous limiting interval, and also ensures that the machine remains within rated values once the short time overload curve is reached.
4. An overall logic to handle the switching between the field forcing, the instantaneous current limiting, the inverse time current limiting, and the normal conditions was introduced.

VII. CONCLUSIONS

In this work, an example was provided to illustrate coordination between excitation control, overexcitation limiter, field overcurrent protection and generator capability. This kind of coordination is important to meet present industry requirements for the use of the reactive overload capabilities of synchronous generators to the full extent. Suggested modifications to the ST1A type exciter model were also presented and the performance of these demonstrated using electromagnetic transient simulation.

VIII. REFERENCES

[1] Reimert, D.; *Protective Relaying for Power Generation Systems*, CRC Press, 2006.

[2] *IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and above*, IEEE Std. C50.13 – 2005, Feb. 2006.

[3] J.C. Agee, R. Beaulieu, G.R. Berube, et al; "Recommended Models for Overexcitation Limiting Devices", *IEEE Trans. on Energy Conversion*, vol. 10, no. 4, pp. 706-713, Dec. 1995.

[4] C.J. Mozina, M. Reichard, Z. Bukhala, et al; "Coordination of Generator Protection with Generator Excitation Control and Generator Capability", in *Proc. 62nd Annual Conference for Protective Relay Engineers*, , pp. 150-164, Mar./Apr. 2009.

[5] A. Murdoch, R.W. Delmerico, 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", *IEEE Trans. on Energy Conversion*, vol. 15, no. 4, pp. 440-450, Dec. 2000.

[6] C.R. Mummert; "Excitation System Limiter Models for use in System Stability Studies", in *Proc. Power Engineering Society Winter Meeting*, IEEE, vol. 1, pp. 187-192, Jan./Feb. 1999.

[7] A. Murdoch, G.E. Boukarim, M.J. D'Antonio, and R.A. Lawson; "Generator Over Excitation Capability and Excitation System Limiters", in *Proc. Power Engineering Society Winter Meeting*, IEEE, vol. 1, pp. 215-220, Jan./Feb. 2001.

[8] *IEEE Guide for AC Generator Protection*, IEEE Std. C37.102 – 2006, Feb. 2007.

[9] *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Std. 421.5 – 2005, April 2006

[10] "Computer Models for Representation of Digital-Based Excitation Systems", *Digital Excitation System Task Force of the Equipment Working Group*, *IEEE Trans. on Energy Conversion*, vol. 11, no. 3, pp. 607-615, Sep. 1996.

[11] A. Murdoch, M.J. D'Antonio; "Generator excitation systems – performance specification to meet interconnection requirements", in *Proc. Electric Machines and Drives Conference*, IEMDC, IEEE International, pp. 317-322, 2001.

IX. BIOGRAPHIES

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Mohindar S. Sachdev (S'63–M'67–SM'73–F'83–LF'97) received the B.Sc. degree from the Banaras Hindu University, India, the M.Sc. degree from Punjab University, Chandigarh, India, and the University of Saskatchewan, Saskatoon, SK, Canada, and the Ph.D. and D.Sc. degrees from the University of Saskatchewan.

In 1968, he joined the University of Saskatchewan, where he is currently Professor Emeritus of Electrical Engineering. His areas of interest are power system analysis and power system protection. Dr. Sachdev is a Fellow of Institution of Engineers (India) and a Fellow of Institution of the Institution of Electrical Engineers (U.K.). He is also a registered professional engineer in the province of Saskatchewan and a chartered engineer in the U.K.