A New Advanced Over Excitation Limiter for Enhancing the Voltage Stability of Power Systems

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Abstract: Mitsubishi Electric has developed an advanced over excitation limiter (OEL) that not only protects the generator field winding from overheating, but also allows the generator to supply reactive power up to its maximum limitation. This in turn allows for the enhancement of voltage stability of a power system by allowing the full range of reactive power supplying ability of a generator to be utilized. Different from the conventional OEL, the limiting margin of the advanced OEL is estimated from on-line computations based on the field current and voltage measurements of the generator. Hence, the "surplus" and "deficiency" that exists with the conventional OEL margin are omitted in the advanced OEL. The advanced OEL is implemented as a function in a digital Automatic Voltage Regulator (D-AVR). In this paper, the principles and features of the advanced OEL are described. A comparison between the advanced OEL and conventional OEL based on numerical simulations is given. Also, a power system application example of the advanced OEL applied to a synchronous condenser is given to show its effectiveness.

I. INTRODUCTION

Providing a means to allow the full range of reactive power capability of a generator to be utilized is very effective for enhancing voltage stability of a power system [1]. The reactive power supplying ability of a generator is usually limited as a function of the temperature rise of its field winding. It is standard practice for excitation systems to include an over excitation limit function (OEL) to suppress the field current for cases when the temperature of the field winding exceeds an allowable level. According to ANSI Standard (C50-13), the permissible thermal overload of the field winding of round rotor generators is given by the solid curve of Figure 1, which assumes that the generator was operating at full rated field current (I_{105}) prior to the subsequent increase in field current. This solid curve shows the relationship between the overload current and permissible time delay, and passes through the following points [2]:

Time (seconds)	10	30	60	120
Field voltage/current (Percent of rated)	208	146	125	112

For salient pole generators a separate standard is not directly specified, but at least the above limits must be satisfied.

The solid curve shown in Figure 1 can be approximated as:

$$t = C1/(If^2 - 1) \qquad (1)$$

where;
t: Time (sec)
If: Field current
C1: Field thermal capability value (more than 30)

Typical over excitation limiters are more strict than given by Equation (1), due to taking account of the following factors:
(1) The temperature of the field winding continues to rise from the point where the OEL starts limiting until the field current reverts to its rated value. Hence, a margin corresponding to the temperature rise is necessary.
(2) If the overload current occurs repeatedly, the initial temperature of the field winding before the OEL operates will be higher than the prescribed value, so a margin corresponding to this "past history" of overload is also needed.
(3) A margin is added to account for the time delays existing in the over excitation detection, operation, etc.
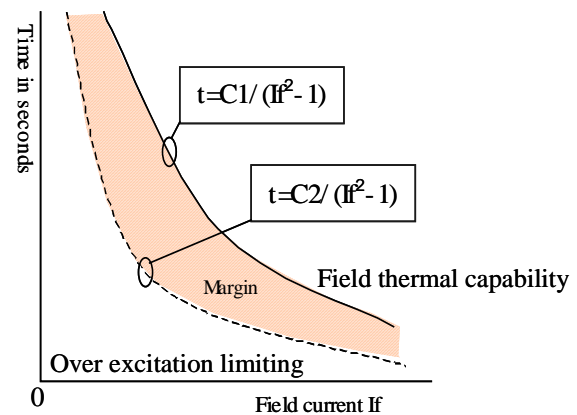

Figure 1. Coordination of over excitation limiting with field thermal capability

The dotted curve shown in Figure 1 shows the relationship between the overload current and permissible time delay for the actual implementation of over excitation limiting function, including all margins. This can also be approximated as:

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$$t=C2/(If^{2}-1) \qquad (2)$$

where; C2 is the limiting value of OEL.

Even the margin between the solid and dotted curves of Figure 1 varies depending on the manufacturer and vintage of the generator unit [3]. Over the many possible operating points of a generator, the margin of the conventional OEL can be in "surplus" or "deficiency" of the generator's actual capability. This is because:

(1) Although the speed of the field current reduction varies depending on the generator, type of excitation system, and the conditions at the time the OEL is engaged, the margin typically applied is based on the slowest speed of the field current decreasing.

(2) Even though a margin is added to account for the "past history" of overloading, if the overloading of field current occurs frequently, then this added margin may be insufficient. Conversely, if the temperature before the OEL operates is lower than the prescribed initial temperature, then the margin would be too large.

Due to the "surplus" margins as described above, the generator does supply reactive power up to its maximum limitation. This can have a negative impact on power system voltage stability. Therefore, Mitsubishi Electric has developed a new advanced OEL that not only protects the field winding from overheating, but also allows the full capability of the reactive power of a generator to be utilized. This is accomplished by omitting the "surplus" and "deficiency" from the margin of the OEL function. The advanced OEL is implemented as a function in a digital Automatic Voltage Regulator (D-AVR). It is a software function that takes its place alongside other functions of a D-AVR such as power system stabilizing (PSS), minimum excitation limiting (MEL), line reactance drop compensating (LDC), cross current compensating (CCC), volts per hertz limiting (VFL), transient stability over excitation boosting (TEB), and high side voltage controlling (HSVC) [4]. The advanced OEL had been applied to a real synchronous condenser for years (described in Section IV) and is playing an important role on regulating power system reactive power.

II. PRINCIPLES AND FEATURES OF THE ADVANCED OEL

Generally, the basic operation of an OEL function can be expressed as:

$$FA+FF+FP+FD \geq C1 \qquad (3)$$

where;
FA: is the thermal accumulation corresponding to the temperature rise after the field current exceeds the rated value of I_{105} (I_{105} is the field current value when the generator voltage is 1.05 p.u. and the generator output power is 1.0 p.u.);

FF: is the thermal accumulation corresponding to temperature rise when the OEL starts limiting until the field current reverts to its rated value;

FP: is the thermal accumulation corresponding to the initial temperature, taking into account past history;

FD: is the margin for compensating various time delays.

Conventionally, FF, FP, FD are taken to be uniform values, therefore the operating condition becomes:

$$FA \geq C2 \qquad (4)$$

where;

$$C2 \geq C1-FF-FP-FD \qquad (5)$$

The OEL begins computing when the field current exceeds $I_{105,}$ and starts to limit the field current when the value of FA becomes larger than C2. Different from the conventional OEL, the new advanced OEL is a computation function (i.e., software) that calculates FF and estimates FP on-line. The principles and the features of the new advanced OEL are described as follows.

(1) Construction

The construction of the advanced OEL is shown in Figure 2. Field current (If) and field voltage (Vf) measurements are used as the OEL inputs. A computation function is used for calculating FA, FF, and estimating FP. A logical operation function is used to control the operation of the OEL based on the limiting condition of Equation (6), and then outputs the limiting signal to the excitation system.
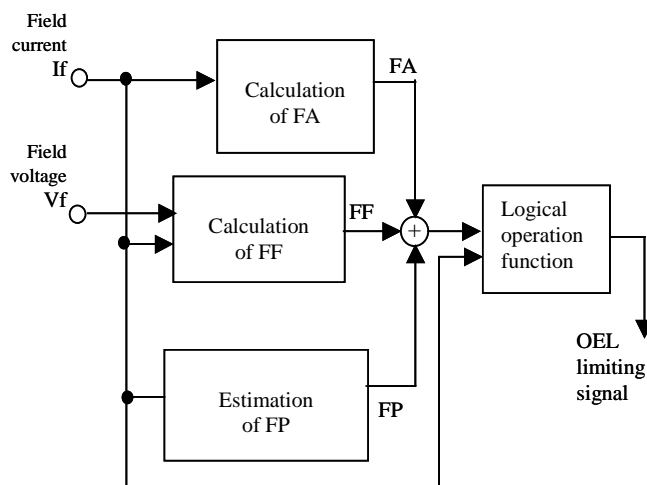
$$FA+FF+FP \geq C1-FD \qquad (6)$$

Figure 2. Construction of the OEL

(2) Principles and Features

Thermal Accumulation FA
The thermal accumulation corresponding to the temperature rise after the field current exceeds I_{105} is calculated the same as the conventional method, using the Equation (7).

$$FA=(If^2-1) \times t \tag{7}$$

Thermal Accumulation FF
The operation behavior of an OEL varies depending on the limiting method. Here, the lower signal select circuit is considered. As shown in Figure 3, when the OEL starts limiting, the field voltage drops instantly and at the same time, the field current decreases abruptly. Although the time, Tr, from where the OEL starts limiting until the field current reverts to its rated value can be calculated exactly, it is not practical since a convergence computation is needed to determine Tr. Here, an alternate approach is adopted to that estimate the field current decreasing time, Tr, according to the inherent crossover frequency ωc of the OEL control loop. Usually, the control target value can be reached within a 1/4 cycle oscillation. Taking account of the time delay of the field current decreasing due to the saturation of the field voltage, and leaving a variation range to the generator field time constant, the field current decreasing time Tr is estimated as 1/2 cycle of ωc by:

$$Tr=(2\pi/\omega c)/2 \tag{8}$$

Furthermore, the decreasing characteristic of field current is approximated by the triangle shown in Figure 4. Then the thermal accumulation (limiting margin) corresponding to the temperature rise during Tr can be estimated by:
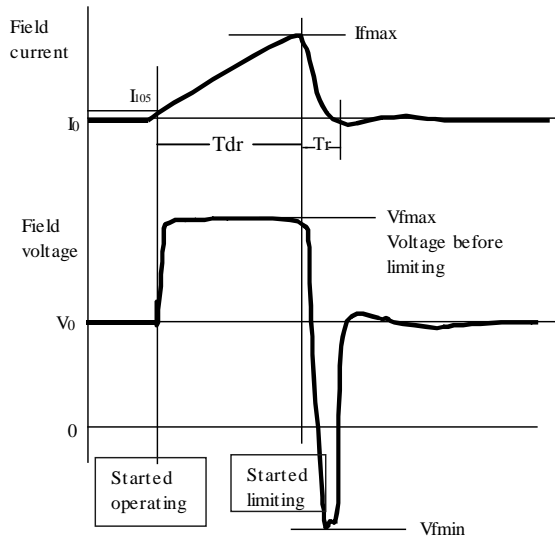
$$FF=(Ifmax^2-1)Tr/2 \tag{9}$$

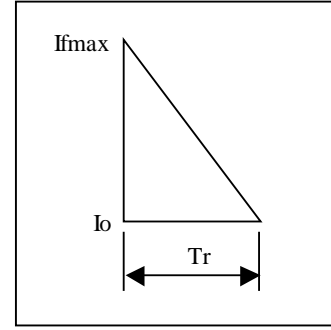Figure 3. Behavior of field voltage and current

Figure 4. Approximated triangle

In this way, the surplus can be omitted from the conventional OEL margin corresponding to the temperature rise during Tr, since the corresponding thermal accumulation is estimated for each generator individually, rather than just leaving an average margin.

Thermal Accumulation FP
The thermal accumulation FP corresponding to the initial temperature is:

$$FP=(\theta_a - \theta_0)/C \tag{10}$$

where;
θ_a: Real temperature of the field winding
θ_0: Base temperature of the field winding
C: Thermal constant

Since the real temperature of field winding is not easy to measure directly, the field winding resistance is used to estimate the real temperature indirectly as shown in Equation (12). The resistance of the field winding can be easily calculated by means of the existing output signals of the AVR, (i.e., field current and field voltage) based on the Equation (11).

$$Rfa=(Vf-Vd)/If \tag{11}$$

$$\theta_a =Rfa(234.5+\theta_0)/Rf_0-234.5 \tag{12}$$

where;
Rfa: Resistance of the field winding
Rf_0: Base resistant of the field winding
Vf: Field voltage
Vd: Slip ring voltage drop

If the real temperature is higher than the prescribed base temperature, the OEL limiting value will be decreased automatically, so that the field winding can be protected from overheating for any repeating or "past history" overload. Conversely, if the real temperature θ_a is lower than the base temperature θ_0, the OEL limiting value will be increased, thus allowing the generator could provide more reactive power if needed.

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III. COMPARISON BETWEEN CONVENTIONAL OEL AND THE ADVANCED OEL BASED ON NUMERICAL SIMULATION

For verifying the effectiveness of the advanced OEL, a comparison between a conventional OEL and the advanced OEL based on numerical simulation is presented.

(1) Simulation Model

The simulation model shown in Figure 5 consists of a simplified generator function and an excitation system digital AVR and OEL function. The simulation condition is to increase the reference value (Vtref) of generator voltage from its rated value to 120% of its rated value.
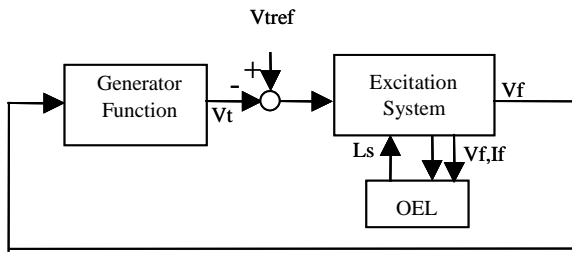

Figure 5. Simulation model (Vt is the voltage of generator, Vtref is the reference value, Vf and If are the field voltage and current, and Ls is the limiting signal of OEL)

(2) Using Conventional OEL

The limiting condition of the conventional OEL for a general excitation system is generally set as:

$$FA \geq 5 \tag{13}$$

The responses of field voltage, Vf, and field current, If, and the thermal accumulation, FA, are shown in Figure 6. As the graphs show, when the field current exceeds I_{105}, the OEL starts computing. When the thermal accumulation, FA, exceeds 5 the OEL starts limiting and the field voltage and current revert to their rated values.

(3) Using Advanced OEL

As described in Section II, the limiting condition of the advance OEL is:

$$FA+FF+FP \geq C1-FD$$

According to ANSI Standard (C50-13), the value of C1 is over 30. Assuming the delay margin FD is smaller than 5, the limiting condition is set as:
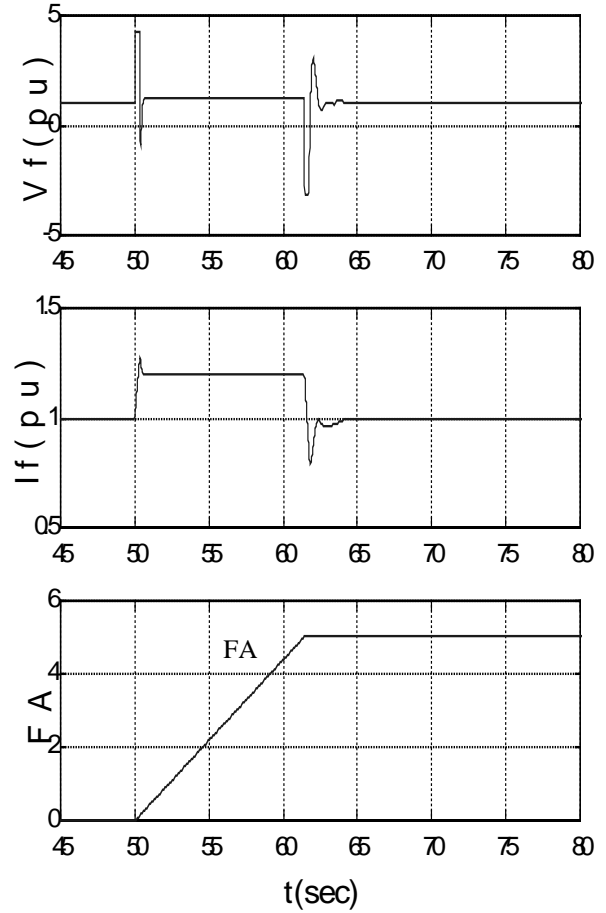
$$FA+FF+FP \geq 25 \tag{14}$$

Figure 6. Results by conventional OEL

The value FP is calculated on-line based on the field voltage and current measurements in the actual implementation. The temperature deviation (i.e., "past history") is also considered here, hence, for the simulations FP is taken to be the fixed values as follows.

Case 1: If the real temperature before the OEL starts operating equals the specified base temperature, then FP=0.0.
Case 2: If the overload current occurred frequently, the real temperature before the OEL starts operating would be higher than the specified base temperature, then FP=23.
Case 3: If the real temperature before the OEL starts operating is lower than the specified base temperature, then FP=-10.

The responses of field voltage, Vf, and field current, If, and the thermal accumulations FA, FF and FP, in each case are shown in Figure 7, Figure 8 and Figure 9 respectively. As the results show, when the field current exceeds I_{105}, the OEL starts computing, similar to the conventional OEL. Then when the sum of the thermal accumulations exceeded 25, the advanced OEL starts limiting, and the field voltage and current revert to their rated values.
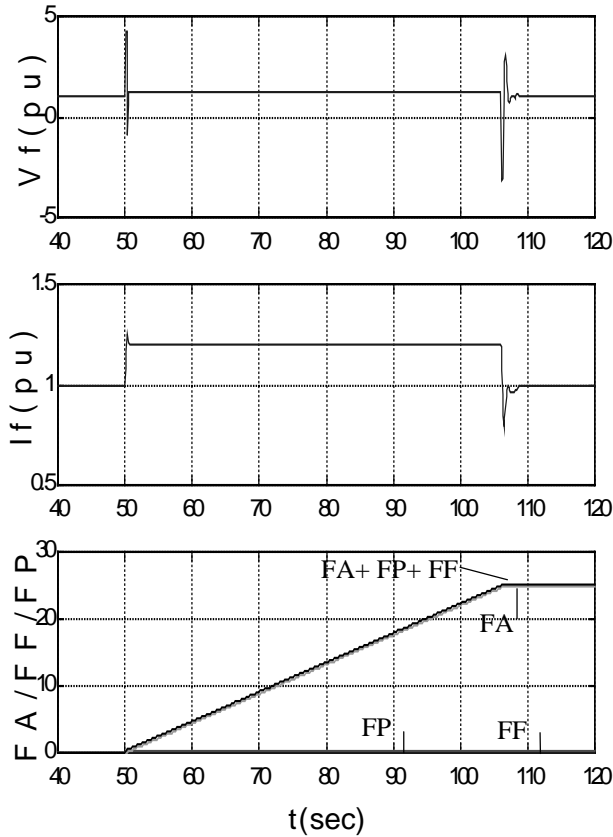
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Figure 7. Results of Case 1 (real temperature before the OEL starts operating equals the specified base temperature)
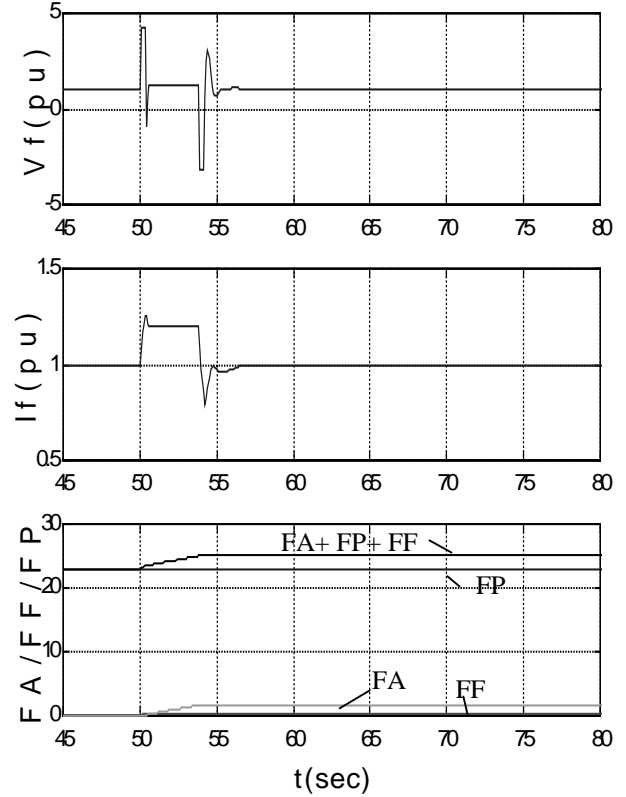

Figure 8. Results of Case 2 (real temperature before the OEL starts operating is higher than the specified base temperature to account for recent past overloads)

4) Comparison

The results for comparison are listed in Table 1. The values of FF are very small since a high response excitation system is used in this simulation model. However, the estimated value of FF is very close to the real difference value ΔFA, where FA1 is the value when the OEL started limiting, FA2 is the value when the field current reverted to its rated value, and ΔFA is the difference of FA2 and FA1. Therefore, this confirms that the estimation of FF is appropriate.

The time values for Tdr (the time when the OEL starts until the limiting is started) are very different depending on the value of FP. In other words, the limiting margin can be regulated automatically according to the initial temperature by using the advanced OEL. In the case of FP=0 (real temperature before the OEL starts operating equals the specified base temperature) and FP=-10 (real temperature before the OEL starts operating is lower than the specified base temperature), the time Tdr is extended to 56.8 and 78.8 seconds. This is much longer than the time by using the conventional OEL (11.7 seconds). This means that the

generator can provide more reactive power if needed, during this extended time. FP=23 (real temperature before the OEL starts operating is higher than the specified base temperature to account for recent past overloads) is for an extreme case where the initial temperature is very high. Here, if the conventional OEL is used in this case, the limiter would start at 11.7 sec after the overload current occurred. With the advanced OEL, the limiter would start within 3.8 seconds hence, the generator winding can be protected more securely.

Table 1
A Comparison of Conventional and Advanced OEL

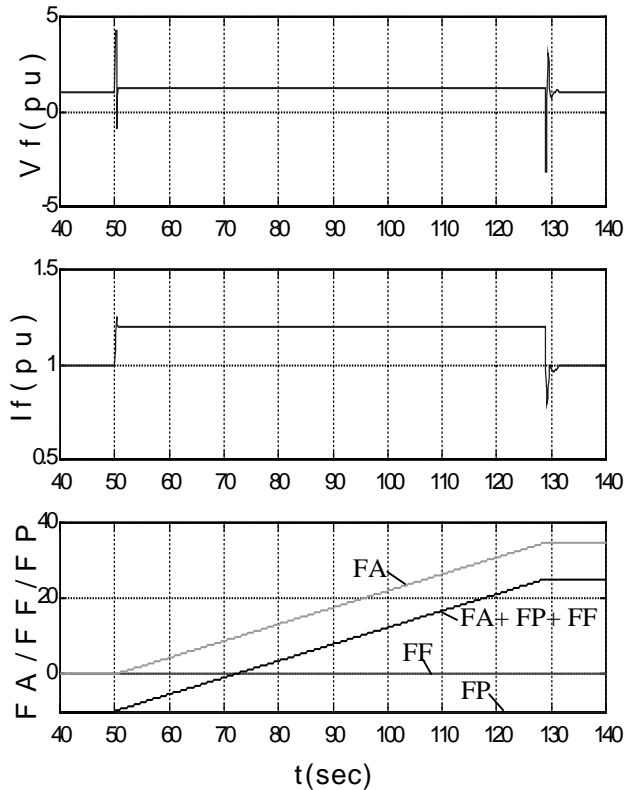| CASE	FA1	FA2	ΔFA	FF	FP	Tdr
OEL	5.00	-	-	-	-	11.7
Case 1 (A-OEL)	24.65	25.04	0.39	0.52	0.00	56.8
Case 2 (A-OEL)	1.65	2.05	0.40	0.52	23.0	3.8
Case 3 (A-OEL)	34.65	35.04	0.39	0.52	-10.0	78.8

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Figure 9. Results of Case 3 (real temperature before the OEL starts operating is lower than the specified base temperature)

IV. APPLICATION OF THE ADVANCED OEL

The advanced OEL has been applied to a real synchronous condenser for a number of years. The synchronous condenser is used to regulate the reactive power of a transmission system and has a rated capacity of 100 Mvar. In an extreme case, this particular synchronous condenser is required to output 300 Mvar of reactive power on a transient basis to maintain the voltage stability of the power system in which it is applied. Thus, there is a strong possibility of overloading the field circuit. A conventional OEL is not able to satisfy both allowing the high level of reactive power output and adequately protecting the field winding. To solve this contradiction, the advanced OEL has been applied to this synchronous condenser. Now, the advanced OEL is playing an important role on regulating the reactive power for this power system voltage stability application.

Test results of the synchronous condenser with the advanced OEL are shown in Figure 10. Here, curve 1 shows the voltage, curve 2 shows the field current, curve 3 shows the summed value of FA+FF+FP, and curve 4 shows the reactive power, all of the synchronous condenser. As the FA+FF+FP reaches its limiting value, the OEL operates to limit the field current. Therefore, the voltage, field current and reactive power dropped instantly, and reverted to another stable state.
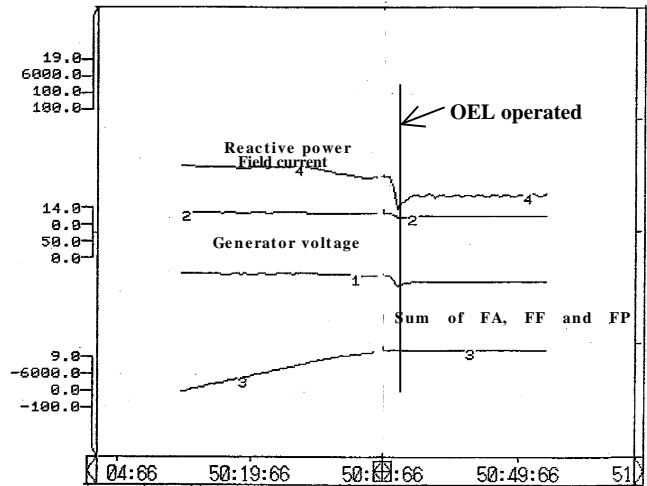

Figure 10. Test results of an advanced OEL applied to a synchronous condenser

V. CONCLUSIONS

This paper introduces a new advanced over excitation limiter (OEL) developed by Mitsubishi Electric. The advanced OEL is implemented as a function in a digital Automatic Voltage Regulator (D-AVR). It is a software function that takes its place alongside other functions of a D-AVR such as power system stabilizing (PSS), minimum excitation limiting (MEL), line reactance drop compensating (LDC), cross current compensating (CCC), volts per hertz limiting (VFL), transient stability over excitation boosting (TEB), and high side voltage controlling (HSVC). The advanced OEL performs an on-line calculation of the thermal accumulations corresponding to the temperature rise during the period from where the OEL starts limiting until the field current reverts to its rated value, and additionally estimates the thermal accumulation corresponding to the initial temperature before the OEL operates. Hence, any "surplus" and "deficiency" contained in the margins of the conventional OEL are omitted from the advanced OEL. Therefore, the advanced OEL is able to contribute to the improvement of power system voltage stability by enhancing the reactive power supplying ability of generator, as well as protecting the generator field winding from overheating.

VI. REFERENCES

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VII. BIOGRAPHIES

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