MAXIMISING ROTOR THERMAL CAPACITY

W.R. Lachs Fellow IEEE w.lachs@ieee.org
Electric Power Department UNIVERSITY of NSW Sydney NSW 2052 AUSTRALIA

ABSTRACT: Not only is there no uniformity in the method adopted for generator rotor overcurrent protection, but the AVR control algorithms do not directly assess the rotor's temperature. Often, after rotor overcurrent protection has functioned following a sharp increase of excitation current, 90% of the rotor's thermal capacity is still unused. A computationally reliable and fast method has been devised for assessing rotor temperature and its rate of change by monitoring each unit's rotor current and voltage. Important benefits can be gained in system operation by utilising this new method to replace existing rotor overcurrent protections.
Keywords: *Rotor Overcurrent Protection, System Voltage Instability, System Reactive Power Balance.*

1. INTRODUCTION

The responses of automatic voltage regulators (AVR) on generators and synchronous condensers provide one of the most valuable resources in dealing with power system disturbances. With any disturbance that abruptly lowers voltage in its vicinity, the AVR initiates a response in immediately increasing the unit's rotor current and raising its excitation and reactive power output. For a large fraction of the disturbances, the field forcing only taps a small proportion of the rotor's thermal reserves when control has been regained and excitation has been reduced to within the rotor's current rating.

The one important exception occurs when unpredictable disturbances have threatened system voltage stability. Initially slightly more than rated excitation is produced in a few units near the region most affected by the disturbance. If effective measures to deal with the disturbance are not taken voltage conditions continue to deteriorate causing excitation currents increase even further. This in turn may activate rotor overcurrent protection that decreases excitation and reactive power output and may even trip generators. This scenario has been reported in the many widespread and lengthy collapses of interconnected power systems throughout the world which have each interrupted tens of thousands of consumers and cost hundreds of millions of dollars. In the analysis of this phenomenon, the action of rotor overcurrent protection on just one unit after sometimes a minute or more has been found to set off a chain reaction in curtailing excitation in adjacent units within seconds. This fast reaction has caused the loss of voltage stability and culminated in power system collapse [1].

2. THE INVESTIGATION

The "nail in the coffin" of system voltage collapse follows the curtailment of excitation on just one rotating unit. In investigating a means for preventing the loss of voltage stability, the key piece of data needed for an automatic arrangement to counter the effects of a threatening disturbance would be to assess the time of sudden reduction of the first rotating unit's excitation.

In reviewing the situation in numbers of power stations and on synchronous condensers, a veritable "hodge-podge" was found with a multitude of rotor overcurrent protections at different power stations. In some instances, the generator would be completely tripped if there were unacceptable periods of excessive rotor current. Delving further into the protection arrangements, not one of them had any provision to assess either the rotor temperature or its rate of rise when it functioned. It soon became clear that it would have been far too difficult to mathematically model each of these overcurrent protection arrangements for evaluating the time to tripping with any excessive rotor current. This revelation prompted a lateral approach to the task, by attempting to assess the rotor thermal capacity from which it might be possible to determine the time a particular rotor temperature would be attained following a sudden increase of rotor current.

3. **ROTOR HEAT RUN TESTS**

The starting point of investigations was to undertake rotor heat test runs on generators at different power stations. To limit the material presented, the result of tests on a 500MW and a 660MW thermal generator are described. These units provided two extremes in that the 500MW unit had an inadequately designed rotor, whereas the 660MW generator's rotor had a generous thermal design [2].

3.1 Heat Run Methodology

After discussions with the Operations Group, heat run tests were devised so as to create the minimal effect on the operation of the generator being tested. Each of these tests was undertaken on one generator at a time, while holding its scheduled MW output but with manual changes of rotor excitation currents. Each of the heat runs involved an abrupt increase of rotor current, following which temperatures were measured at intervals of 30 seconds until a steady temperature was attained. Each of the tests on a generator commenced with a low excitation and involved five step changes of rotor current. Successive step increases of rotor current took place when a steady rotor temperature was reached at the previous step, with the test concluding when the fifth step reached rated rotor current and a steady temperature. There should be no great difficulty for any utility to undertake similar heat run tests on its generators.

3.2 Quantities for Rotor Heating Algorithm

Investigations preceding the rotor heat run tests uncovered the fact the heat flow through the mechanical coupling with the steam turbine raised rotor temperature almost to 50'C when there was no current in the rotor. Consequently variations of ambient temperature have minimal effect on the rotor heating of thermal generators. From the five rotor current step changes conducted with each generator's heat run test, the two parameters required for the rotor heating algorithm could be evaluated. One parameter, the rotor's thermal inertia, is the heating energy required to increase rotor temperature by 1C'. The other is the temperature associated with each rotor current. An analysis of the second function from the heat run results found virtually a linear relationship between rotor heat input energy and rotor steady state temperature. This linearity offered the key to devising a computationally simple rotor heating algorithm and so provided the key to accurately assessing the rate of rotor temperature rise, the temperature it would reach and the time to attain this temperature, following sudden increases of rotor current.

3.3 Rotor Current and Voltage

The primary concern has been to gain a practical solution which was achieved by devising an algorithm that could utilise parameters that are normally monitored when generators are running, namely the generator's rotor current (Ir) and rotor voltage (Vr). In addition, with the simplicity of the algorithm, all required quantities can be computed within seconds of any sudden increase of rotor current.

3.4 Temperatures with Steady Rotor Current

The first component of the algorithm is the expression for the steady rotor temperature for a particular rotor current (the linear plot between heating energy and rotor temperature). These were:

- For the 500MW generator $Ir.Vr = 0.0227(T - 47.7)$
- For the 660MW generator $Ir.Vr = 0.0618(T - 47.2)$

Where T is the rotor temperature in 'C and 47.7'C and 47.2'C were the respective rotor temperatures with zero current in the 500MW and 660MW generator rotors. The variations of rotor resistance with temperature are automatically taken care of by using the product of rotor voltage and current. The error due to brush voltage drop would be of a similar order to the error in temperature measurement, which is usually based on the measurement of rotor resistance.

3.5 Rotor Thermal Inertia

The other constant needed for the algorithm is the rotor thermal inertia, or otherwise the quantity of energy required to increase the rotor's temperature by 1'C. These were evaluated from the heat run tests as:

- For the 500MW generator 3MW.sec/'C
- For the 660MW generator 10MW.sec/'C

These values would probably provide the upper and lower limit of thermal inertia for most thermal generators, because their rotor thermal design should fall between the extremes demonstrated by the 500MW and 660MW generators.

3.6 Philosophy of the Rotor Heating Algorithm

The important breakthrough was a realisation that the curve relating rotor heating to steady rotor temperature provides two important items of information. In the first instance, by knowing the rotor current, its temperature can directly be determined. The second factor is that this curve evaluates the energy being absorbed by the rotor at each temperature. Consequently, when there is a sudden increase of rotor current, its temperature rises until it again attains a settled level. During this period of temperature rise, the energy input per second is known to be Ir.Vr, and the energy consumed by the rotor at each temperature step can be read from the curve. Therefore at each temperature step, the difference between these two values provides the net heating energy per second. Using this information in conjunction with the rotor thermal inertia, it become possible to iteratively evaluate the change of temperature at every second. The starting point of this evaluation would be the temperature corresponding to the rotor current prior to its increase.

The algorithm for the 500MW generator would therefore be:

$$dT = [Ir.Vr - 0.0227(T-47.7)]/3$$

where dT is the temperature rise in one second,

T is the rotor temperature at the previous step and

$T = T' + dT$ with T' as the previous rotor temperature

This iterative evaluation is computational simple and very fast. It can swiftly determine the second by second increase of temperature, following any sudden jump in rotor current.

4. CHECK OF ROTOR HEATING ALGORITHM

With such a computationally simple algorithm, the first task was to test it for accuracy with check evaluations of each of the heat run tests. This involved a computational evaluation of the rotor temperature rise at every second from the time the rotor current was increased until a settled temperature was reached. This comparison between the computation and test results showed all errors were less than 0.5'C, so providing a confirmation of the algorithm, bearing in mind that temperature measurements had a similar level of accuracy [2]. By making a comparison with all heat run tests on every generators, confidence was achieved in the accuracy and practical usefulness of the rotor heating algorithm. With this computational resource it has now become possible to assess the actual thermal capacity of any generator rotor.

4.1 Rotor Temperature with Field Forcing

The key question to be resolved is what is the rotor's thermal capacity for dealing with the high currents due to field forcing by the AVR? There are many variables associated with the problem but each boils down to *the amount of time that the high rotor current can be tolerated*. By its nature, the algorithm is uniquely capable of evaluating the time with any combination of variables. The following variables were examined:

- Levels of rotor temperature prior to field forcing,
- The level of above rated current at field forcing,
- Different levels of final rotor temperature.

The range of times evaluated with the different variables can be found in Reference 2. A selection of these results show how little of the rotor thermal capacity is actually utilised by the existing rotor overcurrent protections, nor ANSI Standard C50.13, with times calculated in Section 4.:

- 120 secs with rotor current raised to 112.5% of rating,
- 30 secs with rotor current raised to 150% of rating,
- 20 secs with rotor current raised to 160% of rating,
- 15 secs with rotor current raised to 180% of rating

For the 500MW with an initial rotor temperature of 80'C, the times for the rotor to reach 135'C are:

- 151 secs with rotor current raised to 112.5% of rating,
- 56 secs with rotor current raised to 150% of rating

For the 660MW generator the times for the temperature to increase from 80'C to 135'C are:

- 230 secs with rotor current raised to 160% of rating
- 120 secs with rotor current raised to 180% of rating
- 64 secs with rotor current raised to 200% of rating

Even if only a portion of this rotor thermal capability can be tapped the present difficulties that are associated with system voltage instability could be substantially ameliorated.

5. ROTOR PROTECTION IMPLEMENTATION

The proposal for retrofitting the alternative rotor overcurrent protection on generators and synchronous condensers provides no insurmountable difficulties. However there are a number of aspects of the retrofit that require careful consideration.

5.1 Microprocessor Control

Simply by using the available monitored quantities of rotor current and voltage on each rotating unit, an associated microprocessor could immediately assess the time when an excessive rotor heating would be reached following an unduly high rotor current, subsequently controlling current reduction.

5.2 Evaluating Rotor Thermal Constants

The rotor heating algorithm from which microprocessor evaluations are made needs two quantities, the rotor thermal inertia and rotor temperatures for different levels of rotor current. These must be individually determined for each rotating unit, using the heat run tests described in Section 3. Before undertaking the heat run tests, it would be wise to check the accuracy of the existing means of recording rotor temperature. For a more satisfactory determination of the rotor algorithm thermal constants, it may be necessary to recalibrate these rotor temperature measurements.

5.2.1 Alternative Rotor Constants

The hydrogen cooling system has the greatest influence on controlling the rotor temperature. On occasions generators operate with the hydrogen pressure lowered. For these generators, two quite different algorithm thermal constants would need to be evaluated, by repeating heat run tests with the reduced hydrogen pressure.

5.3 Time Calibration

The evaluation of the time for the rotor to reach a temperature limit has shown the astounding level of its thermal reserves. In using this proposal, a margin of safety must be provided to eliminate the possibility of excessive rotor temperature. It is suggested that the evaluated time be reduced by a factor of two or three for this purpose. Even with such a time reduction, much longer periods of high generator excitation than at present, would still become accessible. In making a decision on the calibration, the following factors must be given recognition:

- The heating algorithm evaluates the average, not the rotor hot spot temperature,
- The accuracy of the rotor thermal constants is influenced by the accuracy of temperature measurements,
- At the time of an incident, Hydrogen pressure may inadvertently be reduced.

6. CONCLUSION

A rotor heating algorithm is presented which has been devised for practical application, accuracy, simplicity, reliability and speed of computation. The rotor heating algorithm allows an accurate and fast evaluation of the rotor's reserve thermal capacity following a sudden increase of rotor current. In contrast with existing rotor overcurrent protections, the algorithm evaluates the change of rotor temperature and the time to reach a dangerous temperature. By not assessing rotor temperature, existing rotor overcurrent protections do not take advantage of the rotor's thermal reserve capacity. Evaluations have shown that existing protections can leave untapped 90% of rotor reserve thermal capacity when they function.

The rotor heating algorithm requires two generator thermal constants and can assess altered conditions by simply monitoring the generator's rotor current and voltage. The thermal constants can be determined for each generator by undertaking straightforward heat run tests. Consequently there would be little practical difficulty in replacing existing rotor overcurrent protections by a microprocessor associated with each generator that was programmed with the algorithm.

Apart from making better use of rotor thermal reserve capacity, the new facility would be valuable in dealing with severe disturbances that endanger system voltage stability on interconnected systems. A comparison of post-disturbance microprocessor computations would give advance warning of the time available till excitation is restricted on the first rotating unit. This intelligence would be a vital factor in safeguarding system voltage stability and preventing multi-million dollar collapses.

7. REFERENCES

1. W.R. Lachs - "System Reactive Power Mismatch: Analysis and Countermeasures" IEEE Transactions PAS-104. September 1985. pp.2413-2419.
2. W.R. Lachs & D. Sutanto - "Rotor Heating as an Indicator of System Voltage Instability" IEEE Transactions on Power Systems Vol. 10 No.1 February 1995 pp.175-181

BIOGRAPHY:

W.R. Lachs completed his B.E. (Mech. & Elec.) in 1953, M.Eng.Sc.(Elec.) in 1972 at Sydney University and Ph.D in 1992 at the University of New South Wales. In the Snowy Mountains Hydro-Electric Authority from 1953, he worked in communications, contracts and system planning branches. On moving to the Electricity Commission of New South Wales, he gained experience in substation design, system operation, power system auxiliaries, system planning and research & development co-ordination. Since 1988 he has undertaken full-time research at the University of NSW on the automatic control of power system emergencies. He is a member of the IEEE Power System Stability Committee and has made submissions to CIGRE Task Forces 38-02-10 and 38-02-12. Currently he is Newsletter Editor of the IEEE NSW Section and Region 10 PES Chapter Representative. He is an IEEE Fellow.