A Utility Perspective on Under-Excitation Limiters

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***Abstract*--This paper presents a brief review of the experience and perspective of a large Canadian utility with Under Excitation Limiters (UELs). The purpose of the UEL is reviewed along with the results of field testing and modelling. It is concluded that users of these devices must define the dynamic performance requirements of the limiters, by examining the purpose of their installation, and then setting and testing them accordingly.**

Keywords--excitation systems, underexcitation limiters, stability.

I. Introduction

This paper presents a brief review of the experience and perspective of a large Canadian utility with Under Excitation Limiters (UELs). The purpose of the UEL is reviewed along with the results of field testing and modelling. Although we have conducted numerous studies and tests of UEL operation, most of this utility's generators operate without any form of underexcitation limiting.

As modern power systems expanded after the 1940s, design and operation became influenced by the need to overcome stability problems, in the form of steady-state stability limits, transient, or large-disturbance limits and oscillatory or small-signal limits. During the 1950s and '60s utilities and manufacturers responded to these problems with the introduction of continuous-acting voltage regulators and auxiliary excitation controllers and limiters, including UELs. The introduction of high-initial-response (HIR) excitation systems and power system stabilizers (PSS) has led to the mitigation of stability problems to the extent that, on many generating units, there are no practical restrictions on generator outputs based upon stability constraints.

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Early UEL devices, first installed in the late 1940s [1,2], were designed for the purpose of eliminating steady-state and oscillatory stability problems arising from underexcited generator operation. In more recent years, two other reasons have been established to justify their application: prevention of stator end-core overheating, and the prevention of unnecessary operations of Loss-of-Excitation (LOE) relays during system disturbances.

II. The Underexcited Operating Region

The main reasons that generators may be operated in the underexcited region are the following:

Operator Action - Operators may intentionally reduce excitation to maintain a desired high-side system voltage. In some cases, units may be operated at low excitation levels if connected to long, lightly-loaded transmission lines, or to allow them to be used as sources of reactive reserve for contingencies which can initiate voltage collapse. Normal practice, however, is to avoid underexcited generator operation by switching out shunt capacitors or switching in shunt reactors as required.

Excitation System Failures - Failures in the excitation system (e.g. automatic voltage regulator (AVR) reference potentiometer, firing circuitry or other related hardware) can cause the level of excitation to be reduced significantly, forcing the unit deep into the underexcited region. In addition, excitation system failures in adjacent units which result in severely overexcited operation, can force a unit to absorb large amounts of reactive power.

System Disturbances - A major system break-up can result in a limited number of generators connected to an extensive transmission network, necessitating a sudden reduction of generator excitation level (through AVR action) to maintain the system voltage at an acceptable level. In the absence of any limiters, the excitation will be reduced on all AVR-equipped generators, until the terminal voltage returns to the pre-disturbance level.

There are three main issues which must be addressed in examining the steady-state and post-disturbance operation of cylindrical-rotor generators in the underexcited region:

Steady-State and Small-Signal Instability - For operation with fixed excitation (i.e. MANUAL control) the unit tends to become unstable as the excitation level is reduced, due to the reduction in synchronizing torque. This limitation is frequently incorporated in manufacturer-supplied reactive capability data as a curve, or straight line, based on the generator's d-axis synchronous impedance, the per-unit terminal voltage, and possibly, an assumed value for the external system impedance. This simplistic limitation is often used as the basis for the initial settings applied to UEL devices, even when operating on AVR. As excitation is reduced, the damping torque is also reduced, potentially leading to small-signal instability.

Stator End-Core Overheating - In the extreme underexcited region of operation, severe heating of the stator end-core occurs. Manufacturers incorporate this limitation in the capability curve; utilities must respect these limits to ensure that there is no significant loss of life. Operating experience has indicated that in some cases, the detrimental effects are more serious than anticipated and begin in a region well within the manufacturer's capability curve.

LOE Protection Co-ordination - For power system disturbance conditions, transient operation in the underexcited region must be considered in the context of co-ordination with conventional generator loss-of-excitation (LOE) protection settings. LOE relays may also operate for conditions that resemble loss of excitation, such as incorrect operator action or system disturbances.

It is a common belief in the power industry that a UEL, which limits the reduction of excitation, is necessary to provide a solution to each of the three problems discussed earlier: stability, stator end-core over-heating and LOE protection co-ordination. As discussed below, there are often better approaches to solving these problems.

III. Solutions to Underexcitation Operation Limitations

Any solution to the problems outlined above must be considered in the context of the utility's operating philosophy. The elements of this large Canadian utility's philosophy which pertain to excitation systems can be summarized as follows:

- Make full use of capabilities of all installed equipment and maximize reactive power dispatch capability of units to improve operational flexibility.

- Operate units on AVR at all times to allow them to respond automatically to major system upsets and maintain safe levels of all operating quantities, including system voltages, during these disturbances.

- Use static exciters with PSSs on all new units, and for all significant retrofits.

The following discussion highlights how this philosophy affects the utility's approach to dealing with the three main issues associated with underexcited operation.

A. Stability Considerations

Most of the utility's thermal, nuclear and larger hydraulic generators are equipped with static excitation systems and power system stabilizers. The combination of high AVR gains (normally 200 pu E_{fd} /pu E_{t-ref}, steady-state and transient) and high-initial-response exciters with stabilizers alleviates practical constraints on unit loading based on transient, steady-state and small-signal stability. Operation of units without a PSS, or with the unit on MANUAL voltage control, is not permitted for extended periods of time. During major system disturbances, properly tuned AVRs and stabilizers offer considerable advantages over UEL devices.

Setting UELs to respect overly-conservative limits based on fixed excitation, enforces an unnecessary limitation on reactive dispatch capability. If a UEL is placed in service for the purpose of respecting stability limitations, studies are necessary to determine whether the settings provide the necessary rate-of-response to ensure that the unit does not lose synchronism during a large system disturbance.

B. Stator End-Core Overheating

Stator end-core overheating is not an instantaneous problem and detection and protection systems are installed, or can be installed, to handle it, without restricting the availability of the unit to respond to system conditions. Unlike thermal limits in the overexcited region, manufacturers do not normally supply timed settings or damage information for stator end-core overheating. Nevertheless, if UEL devices are used for this purpose alone, then they should alarm only, and not act on the generator excitation, either directly or indirectly. Attentive operators, supplied with the necessary information on both generator and system conditions, are better equipped to deal with the variety of situations which could produce an underexcitation event.

C. *Loss-Of-Excitation Protection Co-ordination*

Traditionally Loss-of-Excitation (LOE) protection has been provided by a combination of exciter-initiated protection (e.g. for inadvertent field breaker opening) and a mho-type distance relay with the circle centered on the negative reactance axis. The unit is tripped if the generator's apparent impedance remains within the characteristic for a selected period of time, typically one second. The selected settings are intended to identify true loss-of-excitation events while not operating for recoverable power swings. In practice, these settings are normally selected using a rule-of-thumb approach, rather than through detailed simulations. The result is that the unit's operating point may not enter the characteristic for a loss of excitation occurring under light-load conditions, or the operating point may enter the characteristic for recoverable transient swings, while the exciter is still operating normally.

UEL devices can provide protection against inadvertent LOE relay operation by raising excitation and forcing the operating point outside of the LOE characteristic. To accomplish this, the UEL must provide fast dynamic response with a setpoint based on the LOE impedance characteristic. A major drawback with some conventional UELs installed on systems with rotating main exciters and slow pilot exciters is that the limit characteristic has to be set with a large margin to cater to transient overreach. Computer simulations are required to confirm that the selected UEL settings provide the necessary performance to meet this goal.

D. *LOE Protection Alternatives*

To deal with the inadequacies of traditional LOE protection, the utility developed a complementary excitation system failure relay, the LER-II relay, to directly monitor the excitation system and act on a failure [3]. The protection can rapidly sense true loss-of-excitation events based on measured exciter output voltage (field voltage) and generator terminal voltage and then initiate appropriate corrective action such as transferring to a standby AVR, to Manual control, or if necessary, removing the unit from the grid if the problem cannot be corrected.

With an LER-II system installed, it is possible to delay the operation of the LOE relay and avoid its potential operation during system disturbances, thereby eliminating or reducing the benefit that might be derived from the UEL under these circumstances.

IV. UEL DYNAMIC PERFORMANCE

Beginning in the late 1950s, the utility tested UEL devices on several hydraulic generators, and later tested UELs on large cylindrical-rotor machines (fossil, nuclear). None of the original devices were left in service, normally due to poor dynamic performance and the lack of a defined requirement. More recently, field tests and simulations have been conducted on a group of units confirming that certain designs can be configured to meet specific requirements successfully. The following discussion highlights some of the results that have been obtained over the years.

A. *Test Results - Rotating Main Exciter Systems*

On the first group of tested systems, the common characteristics were the presence of a rotating main exciter and the presence of long time constants employed in the low-pass filtering of the UEL output signal. Stabilizers were not included in these installations. In almost all cases, whenever the UEL came into action, the unit terminal voltage and real and reactive loading showed severe oscillations that went on for several seconds. These tests were, for the most part, done at excitation levels well within the permissible underexcited operating limit.

Fig. 1a shows results obtained in 1983, on a 635 MVA nuclear unit equipped with a static pilot exciter and an ac rotating main exciter and with the UEL operating with the manufacturer-recommended settings. By adjusting the gain

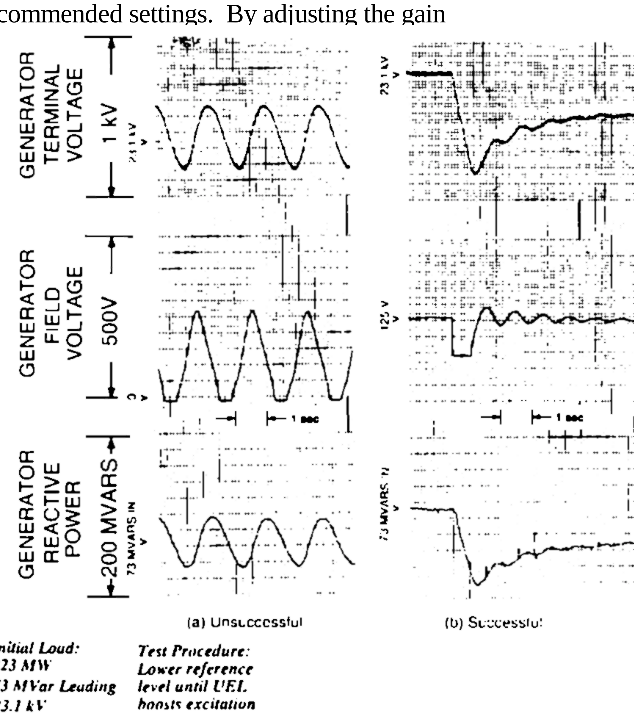

FIGURE 1
Successful & Unsuccessful UEL Test on 635 MVA Nuclear Unit

and time constants of the UEL, the performance was eventually made stable, as shown in Fig. 1b. However, with the stable settings, the response of the UEL was too slow to prevent the LOE relay from operating for certain severe system transients. The UEL was left out of service and the potential still exists for maloperation of the LOE relay.

Subsequent tests performed on a similarly-sized unit with a rotating main exciter and different UEL design, clearly demonstrated that stable high-speed limiting action is attainable on this type of exciter, provided proper damping feedback or correct phase compensation is applied.

B. Test Results - Full Static Excitation Systems

The issues of stabilizer interaction and coordination with LOE protection formed the basis of a series of tests performed on a 353 MVA thermal unit equipped with a digital static excitation system. A simple block diagram of the UEL is shown in Fig. 2. The UEL reference is a function of real power output and terminal voltage entered as a look-up table describing a piece-wise linear limit characteristic. Fig. 3 displays the results of a UEL test on this system. Simulation results were a close match to the field measurements. The advantage of the proportional-plus-integral design of Fig. 2 is that the limiter restores the operating point to the exact setpoint, eliminating the need to introduce regulation margins into the reference settings.

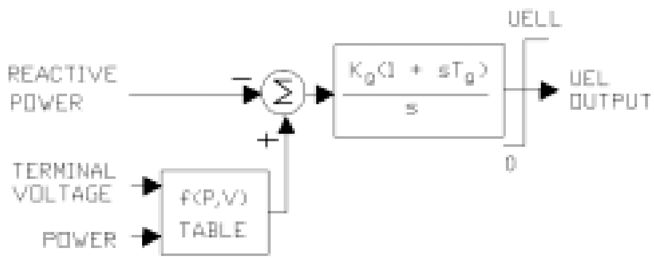

Fig. 2. Simplified UEL Block Diagram

Simulations were performed in which the unit's operating point was forced into the underexcited region bounded by the LOE impedance relay characteristic; this unit is not outfitted with an LER-II relay, and the standard tripping delay of 1.0s is applied to the LOE relay. Fig. 4 displays the locus of generator apparent impedance for a simulation with the UEL in-service with a fixed limit start-point of -0.44 pu. The UEL prevented the apparent impedance from entering the LOE relay characteristic, by producing a 4.5% steady-state terminal voltage rise.

After a review of the system implications, the UELs were placed in service at this station, with the limits set to respect the stator end-core heating limitations of the generator. This level did not impose a restrictive limit on the reactive power capabilities of these units.

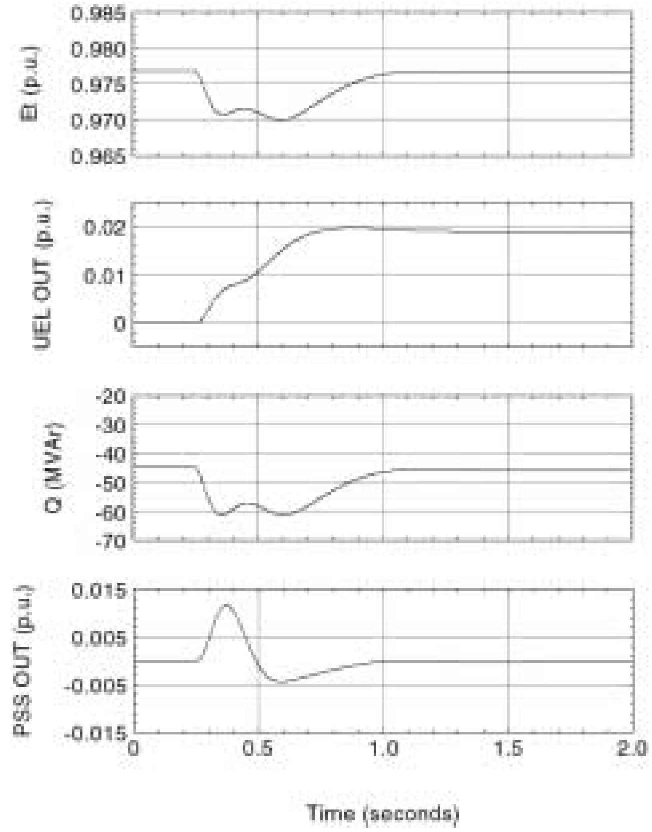

Fig. 3. Response of Digital Exciter UEL

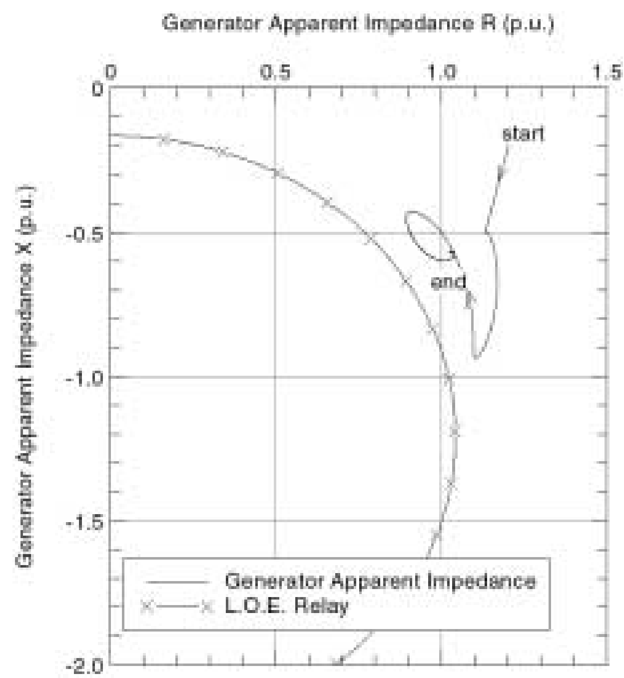

Fig. 4 LOE Characteristic and Impedance Trajectory

V. CONSIDERATIONS IN APPLYING UEL DEVICES

In trying to establish a requirement for installing and setting UELs, utilities must consider the potential adverse side-effects, and these should be weighed against alternative approaches. Potential problems include:

Interaction with other Controls - In an attempt to achieve the high rate-of-response required to deal with stability or protection co-ordination problems, closed-loop UEL response may become highly oscillatory or interact with other control loops [4]. Interactions between UELs and PSSs may reduce the effectiveness of both devices. This problem can become quite complicated where reactive load sharing is enforced between units in a plant, or where inter-machine oscillations are present.

System Overvoltages - If a unit's AVR is functioning properly, maintaining the selected reference level, UEL action will increase generator terminal voltage above its normal levels. This in turn will, by necessity, increase system voltage levels, which are already high [5]. Clearly this possibility should be studied carefully to ensure that it does not result in damaging overvoltages or, through transformer saturation, lead to operation of transformer differential relays, possibly leading to loss of primary load.

Reliability - In any hardware implementation, the potential for failure exists. Adverse effects of any failure must be considered.

It is suggested that utilities considering the use of UELs should have clear answers to the following questions to achieve the desired end results:

- Which problem is the UEL intended to solve at each specific location: stability, heating or protection co-ordination?
- Is the UEL the only, or best, solution to the problem(s)?
- What are the UEL's dynamic performance requirements to solve the problem(s)?
- What are the consequences of the adverse side-effects which are possible at a given location?

VI. SUMMARY and CONCLUSIONS

This paper has addressed very briefly the role of UEL devices on large cylindrical-rotor generators. It is concluded that it is important for users of these devices to define the dynamic performance requirements of the limiters, by examining the purpose of their installation, and then setting and testing them accordingly. It has been the utility's experience, acquired over several decades, that the use of high-speed exciters, high-gain AVRs and power system stabilizers reduces the requirement for UELs. Other utilities which do not apply excitation controls in the same manner may have an increased requirement for UELs, and different operating experience with these devices.

1. The stability of most generating units is greatly enhanced by the use of high-speed exciters and power system stabilizers. The use of both controls makes the full unit capability available to cater to system disturbances and eliminate the need for UELs for stability reasons.

2. Excitation system failures are better handled with a direct-measuring Excitation Failure relay which monitors generator terminal and field voltages. Such a protective device is superior to a standard impedance-type Loss of Excitation relay which may not respond to genuine loss of excitation.

3. If a UEL device must be used in a controlling loop, it should be fast and direct-acting, with a response that has been properly tested on-line at various loads and co-ordinated with other controllers, such as a PSS, provided as part of the excitation system. In addition, accurate models of the device and all other controls on the unit, should be obtained and simulations under various system conditions performed.

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