Coordination of Digital Excitation System Settings for Reliable Operation

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Abstract - **Today's digital excitation systems play a significant role in providing fast and accurate voltage control to the power system. Yet, as noted in the past, undesirable consequences can occur if coordination of limiters and protection, internal and external to the excitation system, is not properly addressed. During extreme operation of the generator and excitation system, the reliability of the system can be jeopardized, resulting in an unscheduled machine trip. The importance of the coordination between the excitation limiters and unit protection becomes obvious; but also important are the proper settings needed to ensure reliable transfer to the redundant excitation controller. This paper will address the importance of coordinating the various settings of the excitation system as well as performance checking the voltage regulator and limiter to ensure reliable operation during disturbance events.**

Index Terms – Excitation Limiters, Voltage Regulator, Excitation System, System Co-Ordination, Protection, Redundant Controller, Loss of Voltage Sensing

I. INTRODUCTION

The Northwestern and Northeastern U.S. blackouts that occurred over the past ten years pointed out the necessity for coordination and testing of the excitation system limiters and protection, as the major outages caused the industry much lost revenue. The blackouts of 1996 and the more recent blackout of 2003 changed practices that would mandate testing and coordination of the excitation system and protection. In 2005, the Energy Act that mandates specific testing and evaluation of the entire excitation and protection system was passed. The North American Electric Reliability Council (NERC) and the Federal Energy Regulatory Commission (FERC) have become the guiding agencies mandating the performance of these tests [1], [2].

II. TYPES OF LIMITERS AND PROTECTION

To properly identify the considerations in coordinating different limiter and protective elements, a brief overview of the most common elements found in today's digital excitation systems is given [3]. The following is a list of the most common limiter and protective functions, along with a brief description of their purpose and the system parameters they monitor:

- *Overexcitation Limiter (OEL)*: Measures field current (or voltage). Attempts to limit the field current to a preset value if the current rises above a set point. The limiting action usually is set to begin based on an inverse timing curve. The OEL limits the heating effect in field windings of the machine. Reference [4] may be used to help define the criteria for establishing the maximum tolerable limit for overexcitation.

- *Overexcitation Protection (OEP):* This is similar to the OEL but instead will apply a trip or alarm signal once the field current (or voltage) is above a set point, typically after a fixed or inverse time delay above the OEL.
- *Underexcitation Limiter (UEL):* Measures watts and vars. The settings for this function typically include setting multiple line segments in a coordinate system where the x-axis is watts and the y-axis is vars. The underexcited portion of the machine's capability curve is used to determine settings, and the element attempts to prevent the machine from dropping into a region of operation below the set curve. The function is used to keep the machine in synchronism or limit end iron heating depending on where the limiting curve is set. There may be separate curves for automatic voltage regulator (AVR) and manual mode.
- *Underexcitation Protection (UEP):* This is similar to the UEL but instead will apply a trip or alarm signal when operating below the set curve of the UEL.
- *Volts per Hertz Limiter (HXL):* Measures generator voltage and frequency. It attempts to limit the ratio of generator volts to generator frequency and typically has an adjustment for changing the volts per Hertz ratio and an inverse timing characteristic. Generator flux density is proportional to the ratio of terminal voltage and frequency. Excessive magnetic flux can be caused by overvoltage or underfrequency and can cause core overheating or breakdown in insulation resistance between the core and laminations. This function is used to maintain generator flux density at appropriate levels.
- *Volts per Hertz Protection (HXP):* This is similar to the HXL but instead will apply a trip or alarm signal. This function typically will operate on an inverse timing curve that is meant to model heating characteristics of a generator or step-up transformer during overexcitation (typically the same curve used for volts per Hertz limiting but set higher for coordination purposes).
- *Overvoltage Limiter (OVL):* Measures generator output voltage and attempts to limit to a preset level, typically with a settable time delay.

- *Generator Overvoltage Protection (OVP):* Measures generator output voltage and initiates an alarm or trip signal when over a specified set point, typically with some settable time delay that is coordinated with the OVL.
- *Generator Undervoltage Protection (UVP):* Measures generator output voltage and initiates an alarm or trip signal when under a specified set point, typically with some settable time delay.
- *Loss of Sensing (LOS):* Monitors the input sensing voltage (generator terminal voltage typically through some transducer) and initiates an alarm or trip when below a set point or, in some cases, if an unbalanced condition exists, typically with some settable time delay.
- *Transfer to Redundant Potential Transformer (PT):* When a loss of voltage sensing event takes place, the voltage sensing inputs are switched to use redundant PTs.

Associated with many excitation system limiter functions are various indications of the status of the limiter function. These indications include limiter picked-up (limiter timing); limiter timed-out, and limiter in control. These indications typically are used in various ways to initiate timers or other monitors to determine that the limiter is functioning properly. If the limiter fails to limit, one of three courses of action is typically taken: initiate a trip signal, initiate a transfer to manual, or initiate a transfer to the redundant controller.

To properly set the excitation limiters and protective elements, the user must understand how the limiters are implemented and how each parameter of the limiter function affects limiter functionality. Fig. 1 illustrates an unscheduled trip of a 2.4 MW brushless-excited generator where the OEL has not been coordinated with the overexcitation protection. Notice that the excitation system provides full boost to the field shortly before the machine is tripped, due to the protection element. In this example, the OEL is programmed for 5 amperes, and the overexcitation protection threshold level is programmed for 5.1 amperes. Insufficient time delay of the overexcitation protection results in improper coordination between the two functions.

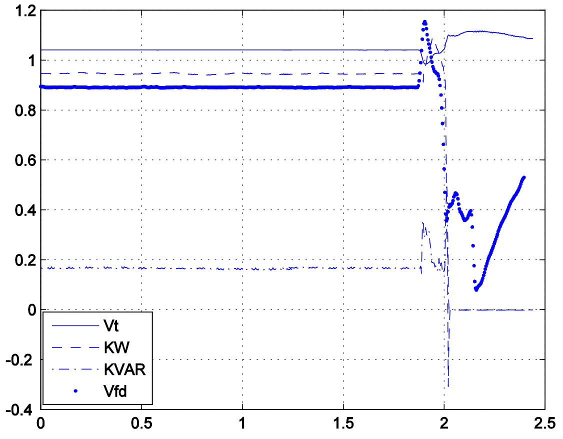

Fig.1. Machine trip due to coordination issues between the overexcitation limiter and the overexcitation protection.

The various excitation limiters included in an excitation system may be implemented as either summing type or takeover type limiters, with user selection of how each limiter is used in the specific application. Whether implemented as a summing type or takeover type, the insertion point within the main regulator loop also may vary. The output of the various excitation limiters may be inserted before the main regulation loop or after the main regulation loop, i.e. directly into the bridge firing command. Within a specific excitation system, each excitation limiter may be implemented in a different manner, and the coordination of each limiter must be reviewed independently based on the implementation.

Figs. 2 and 3 show simplified models for a static excitation system with some of the limiters described above [5], [6]. Note the difference between the summing and takeover type limiters in the model. The choice between these two approaches and the settings used for each will determine overall response of the system.

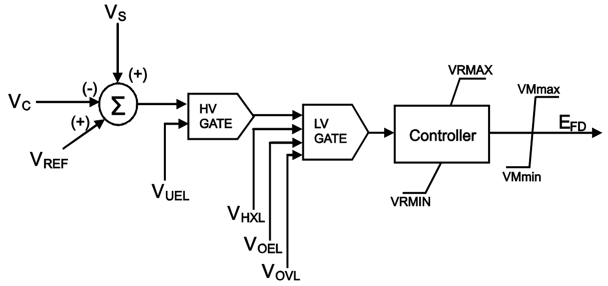

Fig. 2. Takeover Type Limiter.

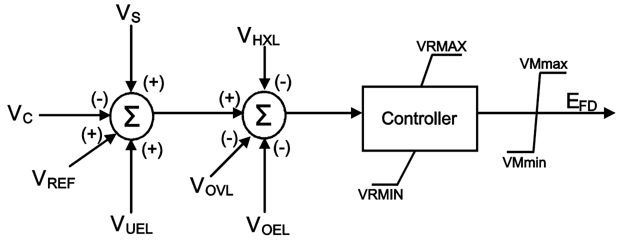

Fig. 3. Summing Type Limiter.

III. PERFORMANCE CONSIDERATIONS

In past blackouts, a range of problems has aided the collapse of the power system in affected areas. Systems were operating in manual control, excitation limiters were not calibrated or tested for validation, and necessary protection was not evaluated against the parameters within the excitation system to ensure proper coordination [7].

The AVR responds to bus voltage deviations that occur during a system disturbance. Where the system voltage deviates from the set point, the voltage regulator provides corrective action by increasing or decreasing the excitation to the field to restore the terminal voltage. Through the selection of proper gain parameters within the AVR, the voltage regulator is tuned to provide optimum response for a wide variety of system issues.

As with the AVR, proper gain parameters must be selected for the individual limiter elements to provide optimum performance. Within each excitation limiter function, there may be additional features or functions that affect how the limiter performs. These may need to be accounted for when trying to coordinate the specific limiter. Each limiter element may include signal input and/or output filters, which could cause additional delays in limiter response if proper settings are not utilized.

Fig. 4 shows a simulated 2% open circuit voltage step response of a 733 MVA, 20kV turbogenerator with a static exciter. Careful tuning of the voltage regulator gains results in very sharp voltage rise with no voltage overshoot. In this example, the voltage recovery time is .7 seconds.

Today, where digital controllers are applied, very precise performance can be achieved with proper gain selection of the various networks to meet the performance goals needed to secure proper coordination between the limiters and protection and fault transfer to the redundant controller [8].

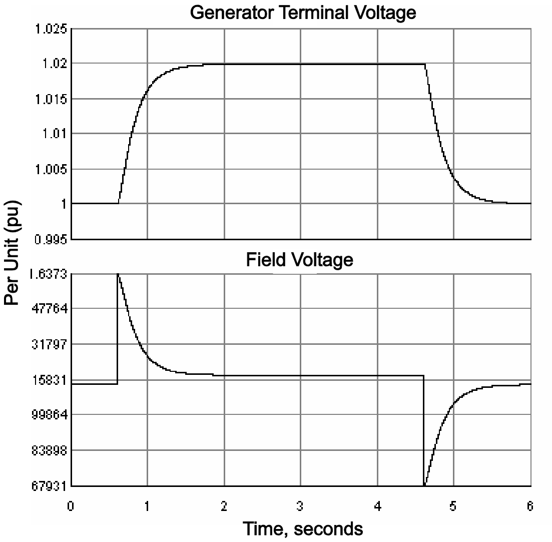

Fig. 4. 2% Voltage Step – AVR Mode.

Fig. 5 shows the limiter response of a summing point type OEL following a 5% online voltage step on a 733 MVA, 20kV turbogenerator connected to the grid through a 20kV/230kV step up transformer and two parallel 10km transmission lines. Fig. 6 shows the limiter response of a takeover type OEL following an identical 5% voltage step on the same turbogenerator.

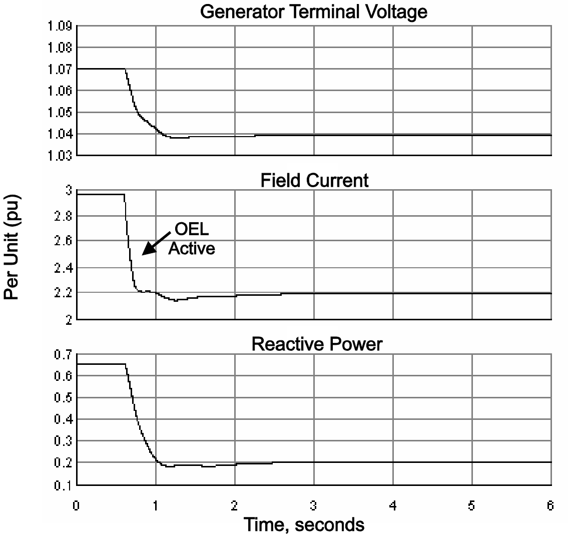

Fig. 5. Summing Type Overexcitation Limiter Response.

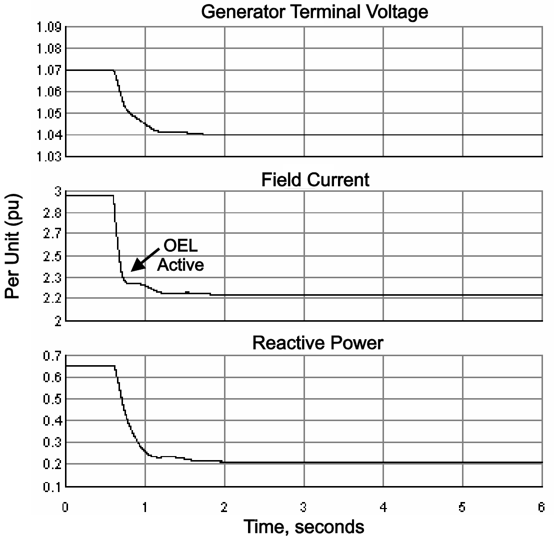

Fig. 6. Takeover Type Overexcitation Limiter Response.

In both Figs. 5 and 6, only the OEL response following the expiration of the inverse time delay is shown. The initial voltage step and subsequent time delay prior to expiration of the limiter's inverse timer have been omitted. The limiters have been tuned to achieve nearly identical response characteristics for this event, having a response time of .6 seconds for the summing type and similar for the takeover type OEL.

The importance of optimizing the response of the voltage regulator and all the limiters is critical to provide predictable performance when disturbance events occur and proper control response is expected.

With the optimized settings identified for the voltage regulator and limiters, the benchmark performance is established for knowing the necessary times needed to coordinate with the protection and transfer mechanisms for the redundant controllers.

IV. COORDINATION OF LIMITERS IN REDUNDANT EXCITATION SYSTEMS

Today's state-of-the-art excitation systems often have redundant controllers with means to automatically transfer between the primary and the redundant controller based on various system events or controller actions. One such means to transfer between controllers is based on the status or interaction of the excitation limiters. More specifically, the transfer occurs because of the primary controller's failure to limit.

Proper coordination of the limiter and protective elements of an excitation system requires specific knowledge of the excitation system, synchronous generator (or motor), and the power system in which the synchronous machine is connected. Additionally, an understanding of the power generation company's protective schemes and any specific regulatory requirements of the local power authority is required to set both the excitation limiter and protective functions [9].

Transfer from the primary to the secondary controller based on excitation limiter status typically is implemented based on failure to limit. To implement this approach, a means to detect failure of the excitation limiter is required. The method to detect failure of the excitation limiter is typically via a protective function, or secondary comparator that monitors the same parameter(s) as the excitation limiter itself. This secondary monitor may be implemented in the various controllers or as a separate device, such as an external protective relay, that is monitoring the excitation system.

When implementing a "failure to limit" monitor, proper coordination is required among the limiter, the protective feature, and the monitor circuit. Because the monitor needs to operate to initiate a transfer between the primary and secondary controller prior to initiating an excitation system trip, it needs to be coordinated with both the excitation limiter and the excitation protection.

To ensure proper coordination among the excitation limiter, the monitor, and the protective features, several criteria are utilized. For proper operation of the failure to limit feature, the monitor must respond to the same parameters as the excitation limiter and must allow the excitation limiter to operate prior to transferring to the secondary controller. The monitor circuit typically includes several parameters similar to the excitation limiter itself, such as a pickup level with fixed time delay - or the monitor may utilize an inverse time characteristic.

Regardless of the implementation of the monitor, two key criteria must be met to ensure proper operation of the circuit. First, the monitor must operate at a level equal to or greater than the excitation limiter itself. Second, the limiter must be allowed to operate and affect the parameter being limited prior to operation of the monitor circuit. The first criterion typically is very easily accomplished as it is simply a direct comparison of two settings. For example, if the UEL consists of a multi-segment limiter curve, the monitor circuit must have a pickup level outside the UEL curve. Fig. 7 shows the coordinated curves of a UEL, Underexcitation Limiter Monitor (UELM), and UEP, plotted with respect to the aforementioned 733MVA turbogenerator's capability curve and steady state stability limit (SSSL). In Fig. 7, the UELM is set 0.03 per-unit (pu) below the UEL's curve, and the UEP is set 0.04 pu below the UELM curve, thus the pickup levels are considered to be coordinated.

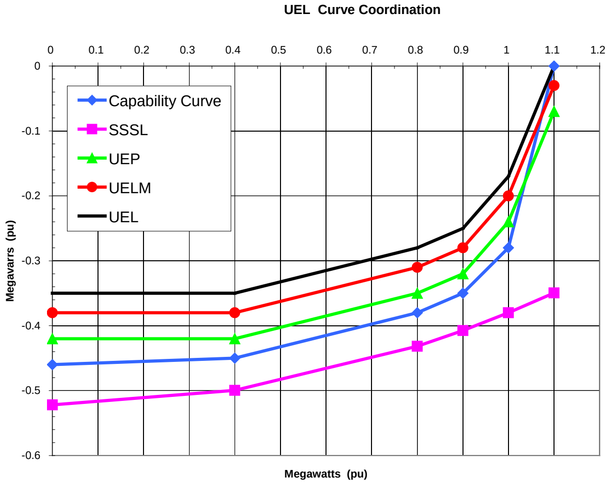

Fig. 7. Coordinated Underexcitation Limiter and Protective Elements.

The second criterion, allowance for the limiter to operate, is not shown in Fig. 7 and can be more difficult to achieve. It requires an understanding of how each specific limiter is implemented in the specific excitation system and an understanding of the system response characteristics. The response characteristics of, not only the main regulation loop, but also the various limiter elements, must be accounted for when selecting time delays for the associated exciter limiter monitor and associated protective elements. Fig. 8 shows the response of an underdamped summing type UEL to a 2.5% reduction in the voltage regulator reference while the turbogenerator is operating at 0.9 pu real power loading. Settings for the various limiter and protection elements from Fig. 7 corresponding to this operating point are shown in Fig. 8. Although there is no intentional delay in the UEL's response to the voltage reference change, the characteristic response of the UEL results in exceeding the UELM's pickup level. Without sufficient time delay in the monitor circuit, a transfer to the redundant controller may have been initiated, although there was no real fault in the main controller.

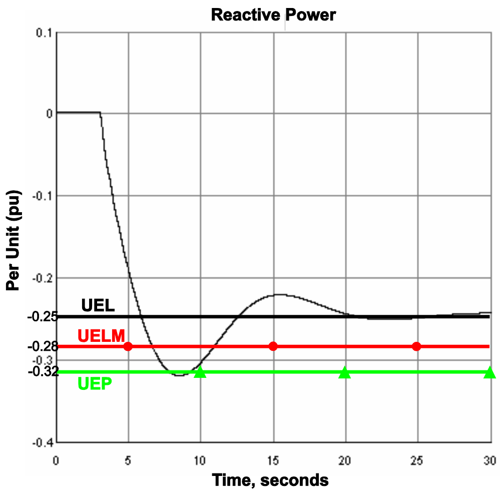

Fig. 8. Underexcitation Limiter Response.

How the specific excitation limiter is implemented (summing type or takeover type) and where the limiter operates in the main regulation loop can significantly change the time the monitor must wait prior to initiating a transfer from the primary to the secondary controller. The monitor circuit typically utilizes the excitation limiter's 'timed out' status as an indication that the limiter either should be in control of or affecting the excitation system's firing command. However, depending on the type and implementation of the limiter, the time delay in the excitation system responding to the limiter following the timed out status can vary. Figs. 9 and 10 show the response of a summing type and takeover type OEL, respectively, to a loss of voltage sensing event where the transfer to redundant sensing transformers and the transfer to manual features have been disabled. Each of the limiters is implemented as shown in Figs. 2 and 3 and tuned to a small signal disturbance as shown in Figs. 5 and 6. Based on the specific implementation and tuning of each OEL type, the response to a large signal event, such as a loss of voltage sensing event, can be significantly different for each limiter, although both types appear to have nearly identical response characteristics for small signal disturbances. The time delay associated with the monitor must take these specific characteristics into account or an undesired transfer from the primary to the secondary controller may occur.

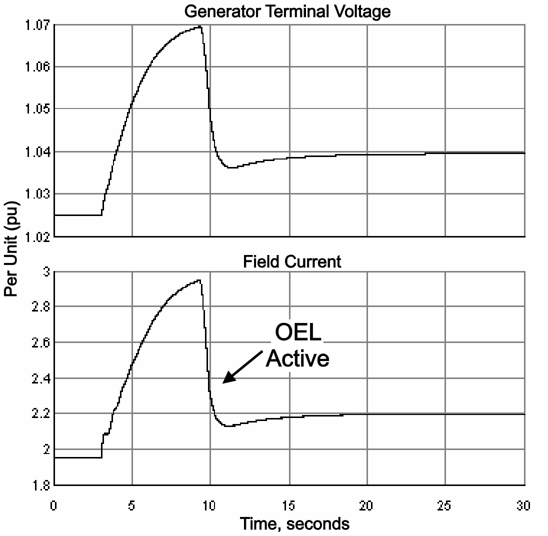

Fig. 9. Summing Type Overexcitation Limiter Response to Loss of Sensing.

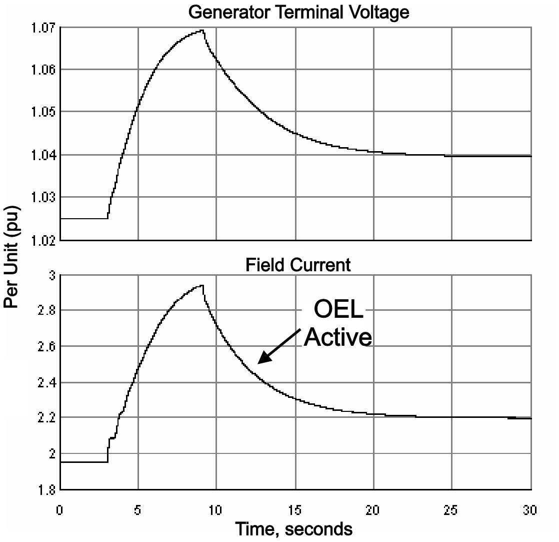

Fig. 10. Takeover Type Overexcitation Limiter Response to Loss of Sensing.

Each excitation limiter in the system that will be monitored must be reviewed to ensure proper coordination of the failure to limit function. Following a transfer from the primary to the secondary controller, proper coordination of the limiter and protective functions must be maintained. Coordination among the limiters, failure to limit monitor, and protective features must be maintained in both the primary and secondary controllers and throughout the transfer. To ensure proper coordination of the excitation system, each excitation limiter must be reviewed to ensure the limiter in the primary controller is allowed to operate prior to a transfer to the secondary controller. Additionally, if such a transfer occurs, the excitation limiter in the secondary controller must be allowed to operate prior to operation of the excitation system's protective features.

V. EXCITATION LIMITER VERSUS PROTECTION SETTINGS

The proper coordination of limiters and protective elements within an excitation system is necessary to ensure proper startup and operation during an abnormal system event. New digital excitation systems include advanced features. These features can include:

- Multiple limiter levels
- Multiple timer outputs
- Offline/online settings groups
- Cooldown compensation
- Settable hysteresis
- Flexibility to apply limiters as either summing or takeover type
- Recalibration inputs

Generally, any function that incorporates both limiting and protection must be coordinated such that the limiting action has a chance to act prior to the protective element causing a trip. This can be accomplished by applying appropriate set points and time delays for limiting and protection, but becomes more complex in systems that allow multiple settings levels, off-line/on-line settings groups, cooldown effects, and the use of multiple inverse timing curves. Different types of limiter and protection elements must be coordinated with each other [9]. On-line and off-line operation requirements have different considerations.

A. Off-line Coordination (No Load condition)

In off-line conditions, field current will be relatively low compared to loaded conditions, so the off-line settings for overexcitation should be set accordingly. Because field current will directly affect generator output voltage, the HXL/protection, as well as the OVL/protection should be coordinated with the OEL/protection. In the off-line case, the OEL typically will act first. In systems with no off-line setting for the overexcitation element, the overvoltage, volts per Hertz, or instantaneous field current element is used for coordination of transfer and trip.

Since the HXL is set based on a ratio of voltage and frequency, the OVL can be used to limit terminal voltage in cases where limiting of the output voltage is desired but the voltage-to-frequency ratio is not above the specified set point.

The OEL setting should be considered when determining the OVL and protection values. Depending on the settings used, both limiters could be active for a particular event. The generator’s saturation curve can be used to establish settings so that the desired limiter acts first. In some cases, the overexcitation elements will have on-line and off-line settings, while the overvoltage element will not. It may be best to set the overvoltage element for desired limiting and protection in the off-line condition and utilize the multiple settings groups of the overexcitation element for proper coordination. In all cases, the protective elements must have set points and time delays that allow limiters to operate and allow for increases in field current and generator voltage from forcing conditions.

B. On-Line coordination (Loaded condition)

When on-line, it is assumed that the generator is connected to the grid. Because not all elements will use off-line and on-line settings, many of the same considerations discussed in the off-line coordination section are valid when determining on-line settings.

The on-line settings for the OEL and protective element will be set for values slightly higher than full load field current. The OVL and protection, HXL and protection, and on-line field current (or voltage) protection must be considered when determining the on-line settings of the overexcitation element. The volts per Hertz element and overvoltage element typically do not have on-line and off-line settings. When setting these limiter set points, it must be determined which limiter will have priority. Consideration should be given to what each limiter is designed to do and what is most important to protect in the particular system. The OEL is designed to prevent field overheating, while the HXL is designed to prevent core overheating. A generator saturation curve can be used to help coordinate these set points. The protective functions for overexcitation, volts-per-Hertz, and overvoltage are backups to the limiter functions and should be given the same considerations as the limiters with assurance that the protective functions allow the limiter functions to act. When the generator is loaded, saturation effects will be more apparent and greater care should be taken when coordinating the field current with generator output voltage.

The UEL should be coordinated with undervoltage protection and underexcitation protection. The protective elements should be set to allow the limiter to respond. The generator’s capability curve should be used to determine these settings.

As an example, consider the voltage step shown in Fig. 11 (The initial voltage step and subsequent time delay prior to expiration of the limiter’s inverse timer have been omitted). The OEL and OVL (the HXL would be similar to the OVL), have been coordinated such that the OEL is in control. During this event, both limiters will be active and protection will pick up.

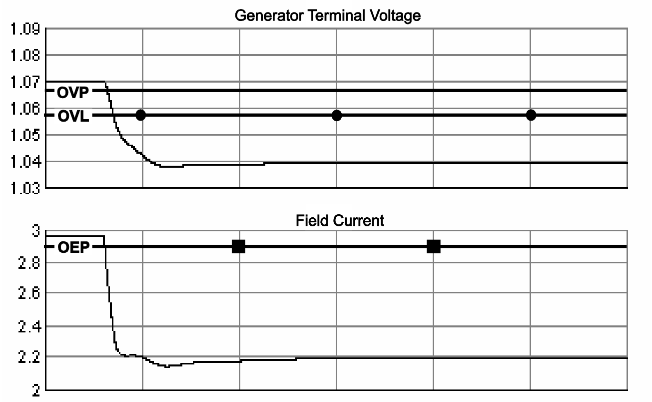

Fig. 11. Coordination of limiters with overexcitation limiter in control.

Some functions do not require special consideration for on-line or off-line operation and may not need to be coordinated directly with other limiter or protective functions. These elements send alarm, transfer, or trip signals for specific system events. These might include diode/SCR failure, rectifier bridge overtemperature, field ground detection, and field overtemperature. In these cases, coordination typically is not required because the system event being monitored is one in which limiter functions will be ineffective.

VI. TESTING FOR VALIDATION

Today, strong emphasis is placed on testing the complete excitation system to be sure proper coordination is achieved. In many regions of the United States, NERC has mandated the necessary testing to validate the various functions discussed in this paper. The only way to validate the desired performance is through testing of the excitation limiters, protection, and transfer of the redundant controller during commissioning. Figs. 2-4 demonstrate the type of voltage regulator and excitation limiter responses needed to provide precise control when the supplementary controls are expected to operate.

VII. CONCLUSION

Improper coordination of limiters and protection and faulty transfers between redundant controllers have resulted in power failures. Since 2005, the Energy Act, via the regulatory agencies such as NERC and FERC, has stressed the importance of testing and qualifying the operating settings of the excitation system with related protection settings [1], [10]. This paper provides insight regarding the coordination of excitation limiters, protection, and transfer to redundant controllers to ensure proper operation of the equipment during disturbance events. The confirmation of settings during commissioning will help to ensure proper and reliable operation when unexpected system events occur.

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IX. BIOGRAPHIES

Richard C. Schaefer, a Senior IEEE Member for 16 years, holds an AS degree in Engineering Technology. He is Senior Application Specialist in Excitation Systems for Basler Electric Company. Since 1975, Rich has been responsible for excitation product development, product application, and the commissioning of many plants. He has authored technical papers for numerous conferences including IEEE Power Engineering Society, IEEE IAS Pulp and Paper, EPRI, and IEEE Transactions on Energy Conversion and IEEE Transactions on Industry Applications publications. He has been involved with power plants for longer than 25 years.

Don Jansen graduated in 1993 with a BSEE from University of Missouri-Columbia and has been employed with Basler Electric since 1995, currently as Principal Electrical Engineer. He spent 3 years in commissioning and troubleshooting of static excitation and voltage regulation equipment and the last 10 years in the design and integration of digital excitation systems.

Shawn McMullen is Senior Electrical Design Engineer for Basler Electric Company and holds a BSEE from University of Colorado-Colorado Springs. Since 1999, Shawn worked in digital camera design for vision-for-machine applications and, for the past 3 years, in electronics design and modeling for excitation systems. He is a member of IEEE. Shawn has conducted product training and has taught at Basler Electric’s Power Control and Protection Conference.

Pranesh Rao, a member of IEEE, is a Principal Engineer with Basler Electric Company. He has an MS degree in Electrical Engineering from the University of Missouri-Rolla. Since 1999, he has developed products in the areas of excitation system controls, protective relaying and genset controls. Pranesh's areas of technical interest are digital controls, power system analysis and digital signal processing.

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