VOLTAGE VERSUS VAR/POWER FACTOR REGULATION ON SYNCHRONOUS GENERATORS

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Abstract - When paralleled to the utility bus, synchronous generators can be controlled using either terminal voltage or var/power factor control. Selection is dependent upon the size of the generator and the stiffness of the connecting utility bus.

For large generators where the kVA is significant, these machines are usually terminal voltage regulated and dictate the system's bus voltage.

When smaller terminal voltage regulated generators are synchronized to a stiff utility bus, the system voltage will not change as the smaller generator shares reactive loading. However, if the system voltage changes significantly, the smaller generator, with its continuous acting terminal voltage regulator, will attempt to maintain the voltage set point. As the voltage regulator follows its characteristic curve, it may cause either over or under excitation of the smaller generator.

Excessive system voltage may cause a small generator to lose synchronizing torque, while low system voltage may cause excessive heating on the generator or excessive overcurrent operation of the excitation system.

Maintaining a constant reactive load on the smaller generating unit can reduce the generator field current variations and, thus, reduce the maintenance of the collector rings and brushes.

This paper illustrates the effect of changing system bus voltage on small generators utilizing voltage versus VAr/power factor regulation.

INDEX TERMS: Synchronous generator, excitation systems, voltage regulators, var/power factor controllers

I. INTRODUCTION

When synchronous generators are tied to a utility bus, conditions may exist in which it is not desirable for a generator to use a terminal voltage regulator with reactive droop compensation. These conditions occur where the transmission or distribution voltage may be sensitive to local load fluctuations. The bus voltage may be normal in the early morning, but drops progressively through the day as system loading increases. In other cases, high reactances in the transmission and distribution line can cause undesirable voltage drops with increased system loading. This reduces the available voltage at the load, forcing local area generators to supply more VArs into the utility bus to meet the demands of the system.

Depending upon the impedance of the transmission or distribution line at the area of the local generating station, and the voltage regulation of the system bus, a smaller generator tied into the utility bus can become either severely overloaded or underexcited. The severity depends upon the magnitude and direction of the system voltage change.

II. TYPES OF EXCITATION SYSTEM REGULATION

Voltage variations are not uncommon in the utility system. When they are minor, the reactive droop compensation within the voltage regulator will assure reactive load sharing between the generator and the interconnected bus. This prevents large changes in reactive current for any one generator. Excessive reactive current can result in either overload or loss of generator synchronism. Reactive droop compensation is accomplished by the addition of a current transformer in one of the generator output leads. With the proper orientation of this signal into the voltage regulator sensing circuit, the control system becomes sensitive to reactive current flow. The compensation circuit has the same effect as adding approximately 10% impedance in series with the generator whose automatic voltage regulator provides 1/2% voltage regulation.

In Fig. 1, a generator is equipped with a solid state voltage regulator having reactive voltage droop compensation. The graph illustrates the effect of bus voltage changes on the reactive/ampere load on the generator. If the bus voltage drops by 6%, the reactive/ampere generator load will change from zero to 70%. A further decrease to 10% could exceed the kVA rating of the generator, causing excessive heating in the field winding and the power semiconductors of the excitation system. The increase in field heating is proportional to the increase of lagging reactive/ampere load.

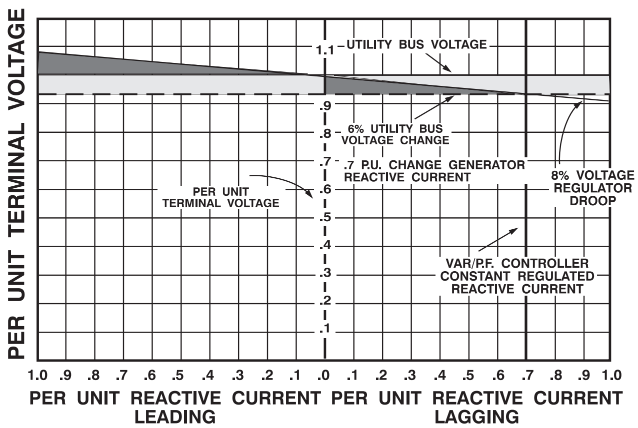

Fig. 1. Voltage Regulator Droop Versus Var/PF Control Regulation

Fig. 1 also illustrates a condition where the bus voltage may increase, causing a leading power factor condition on the generator. Here, insufficient reactive droop compensation may cause the generator to become underexcited, and the voltage regulator circuit can cause potential loss of machine synchronism. To avoid these possible scenarios, a maximum excitation limiter is used to prevent excessive rotor heating when the bus voltage drops very low, while a minimum excitation limiter is utilized to prevent generator potential loss of synchronism when the system bus voltage rises excessively.

For these conditions that can dramatically affect small machine performance, a more favorable method of control is the use of a VAr or power factor control. There are several schemes used today from a continuous analog-type, a SCADA or meter relay output contacts scheme (a non-continuous acting method) to digital regulators. Any of these methods will cause the generator to be regulated at a programmed quantity of VArs or power factor. The major difference between the schemes is the response time of the controller to modify the voltage set point. In Fig. 1, the var controller is used in lieu of the terminal voltage regulator with reactive droop compensation. Notice the effect of bus voltage changes on system vars in voltage regulation mode, while the var controller can be set to regulate the generator at a programmed level of 70% vars and maintain it, regardless of bus voltage changes that may occur. The controller provides essentially infinite droop.

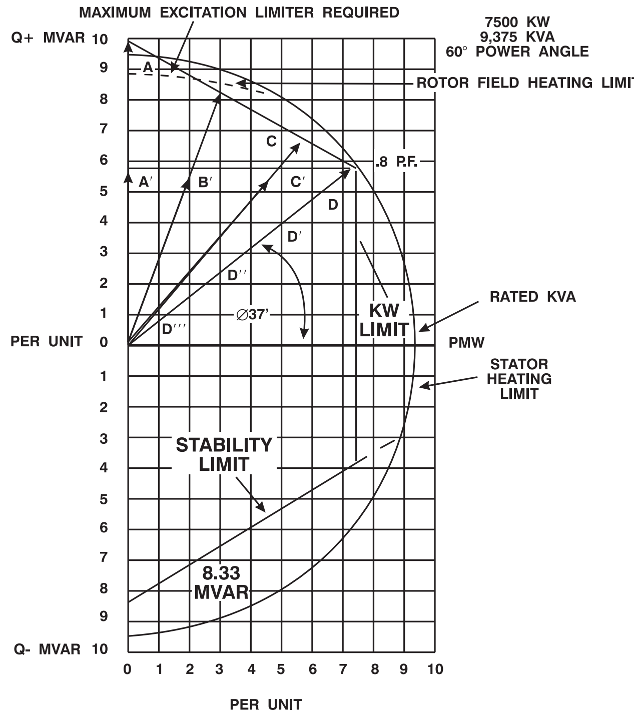

Fig. 2. Generator Capability Curve

Fig. 2 is used for explanation in describing the controller's operation. A vector 0-D is used to represent full 0.8 power factor output of a generator. With "var" control, if kilowatts are decreased progressively, the vector O-D will move in a horizontal manner to 0-C', 0-B' and finally 0-A', regulating the var quantity regardless of kW changes. Changing the controller to regulate "Power Factor " causes the cos ∅ to be regulated. As kW decreases, the operating point will move proportionally from D to D' and finally to D", decreasing the "var" component, but maintaining a constant angle ∅.

III. SYSTEM TESTING AT THE PORTAL POWERHOUSE

To illustrate the system performance variation between voltage regulation with the voltage set point reactive droop compensation versus var/power factor control, tests were conducted on a 10.4 MW hydro-turbine generator. The generator utilizes a 100 kW static exciter regulator equipped with an automatic voltage regulator and reactive droop compensation working directly into the main field. Also included is a minimum/maximum excitation limiter and a var/power factor controller.

The machine is located at the Portal Powerhouse in Central California on the western slopes of the Sierra Nevada Mountains. It derives power from the upper San Joaquin River basin drainage area. The generator is a lone, unattended machine, connected at the end of a radial line. Portal PowerHouse generates at 4,800 Vac then is stepped up to 34.4 kV into a medium voltage distribution line. The area distribution voltage is dependent upon the utility bus voltage. The change in the bus voltage can cause significant reactive current to flow between the Portal generator and the interconnected bus. Based upon these conditions, the excitation system was equipped with var/power factor control. See Fig. 3.

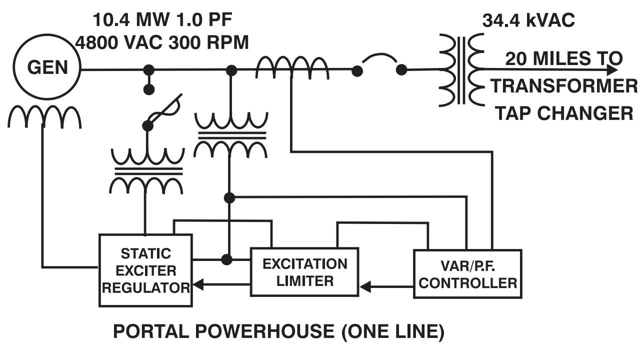

Fig. 3. Portal PowerHouse (One Line)

Three tests were performed on the generator to illustrate the system performance between voltage, var and power factor control. During the test, transformer taps at the 34.4 kV distribution level, approximately 20 miles from the Portal Powerhouse, were raised and lowered to adjust the system voltage. The data collected illustrates the effect of the system voltage change on the 10.4 MW generator. Performance data included generator terminal voltage and line current, generator Mvar and MW, phase angle between the generator line to line voltage and line current, system voltage measured at the transformer tap changer, and generator field voltage and field current.

A. Terminal Voltage Regulator

For the test, transformer taps were moved to eight different settings, four lower, a neutral and three raise. Each representing a 2 1/2% voltage step change. After the data was recorded, all generator quantities- were normalized to reflect 100% MW, zero Mvars - 100% MVA, at rated field current and voltage, rated generator terminal voltage and normal system line voltage.

Fig. 4 shows the per unit change in generator voltage measured at the terminals of the machine versus field voltage and field current.

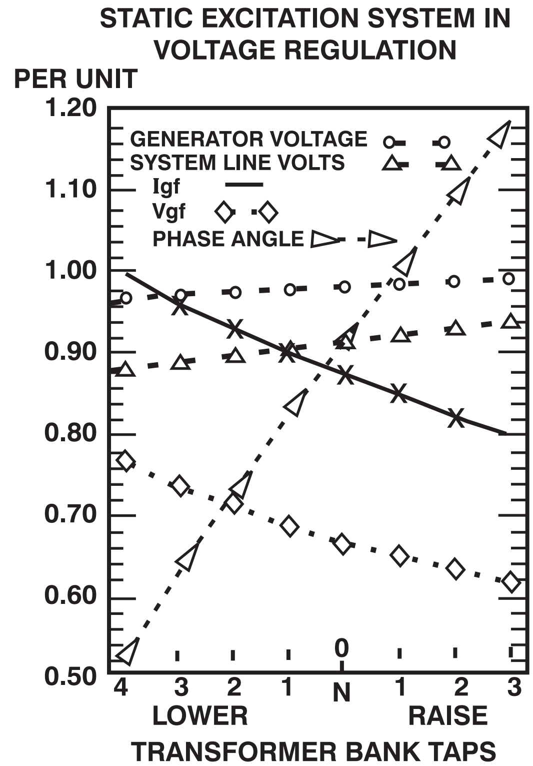

Fig. 4. Per Unit Change in Generator Voltage

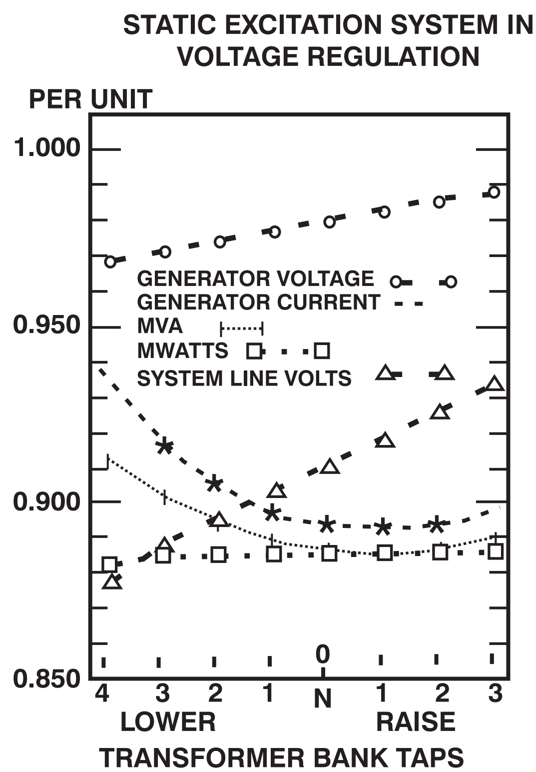

Fig. 5. MW Component

The generator output voltage changed 2.0% while field excitation changed approximately 25% over the same range. As the transformer taps were progressively reduced, the automatic voltage regulator sensed the lowering system voltage and reacted by pushing more dc power into the field. When the transformer tap changed to its highest position, system voltage measured at the tap changing transformer likewise raised. Here the automatic voltage regulator reduced the field excitation into the rotor to reduce the generator voltage. As the automatic voltage regulator attempted to keep the generator voltage constant, the generator reactive current flowed into the generator (VArs buck) thus causing the phase angle between the generator voltage and current to increase.

Fig. 5 shows that the component of the MW remained essentially constant as the governor regulated the power from the turbine. MVA, however, changed approximately 3% as the voltage regulator varied its output response to maintain generator terminal voltage.

Generator line current exhibited the familiar generator V curve characteristic as field excitation is varied by the command of the automatic voltage regulator. The reactive current magnitude of the generator output is extremely high at the minimum transformer tap (vars boost) due to the large voltage difference between the generator and bus voltage. As the transformer tap is moved to the maximum position, raising the bus voltage, the action of the automatic voltage regulator reduces the field excitation. This action again creates a voltage difference between the generator and bus voltage, causing the reactive current magnitude to be high but in the opposite polarity. Here, the vars are being absorbed into the generator (vars buck).

The difference in generator voltage and system bus voltage is noted in Fig. 5. While the voltage regulation of the generator is 2.0%, the regulation of the system bus voltage varied 6%. The difference in regulation, is due to the voltage drop caused by the reactances in the distribution line between the generator and the changing transformer tap, and the impedance of the generator step up transformer. Table 1 illustrates the percent change of the various quantities as the transformer tap range is moved through eight different positions.

B. Var Control

Upon completion of the first test, the operation of the static excitation system was switched from voltage regulation to var control. In the VAr mode, the excitation system was regulated to keep the reactive current constant. New performance data was generated using the same transformer tap range. Figs. 6 and 7 illustrate the effect of VAr control on the generator while Table 2 tabulates the data and shows the percentage change in the measured quantities.

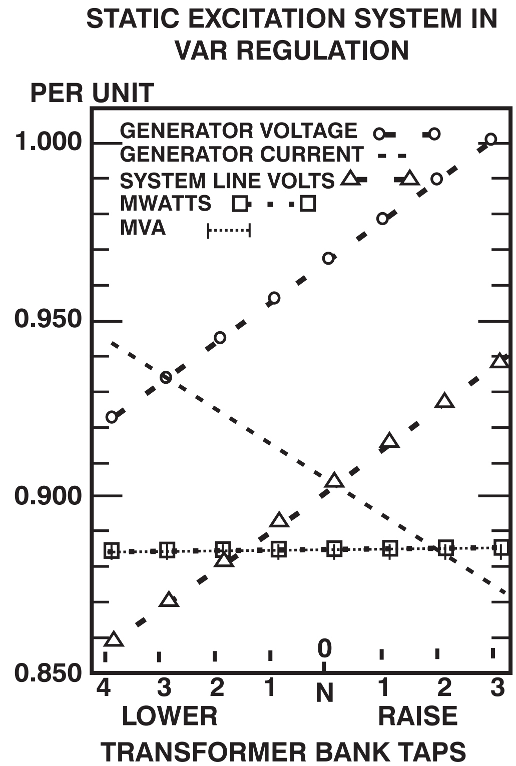

Fig. 6. Var Control Test Per Unit Change in Generator Voltage

Phase Angle Change	Generator Voltage	System Bus Voltage	Generator Current	Field Current	WATTS	MVA
20°	2.0%	6.4%	5.4%	25.3%	0.53%	2.7%

Table 1. Change for Generator Quantities in Voltage Regulation Mode

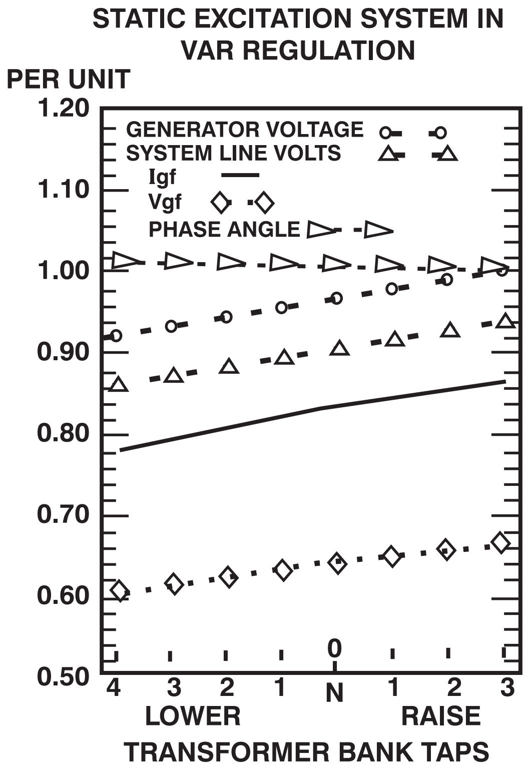

Fig 7. Var Control Test Machine Phase Angle, Minimum Change

In VAr mode, tests were conducted in an identical manner to the voltage regulator mode. Fig. 6 shows a substantial difference in the reaction of the generator terminal voltage to the change in system voltage, as compared with Fig. 5. Since the generator voltage was no longer the sensed parameter of the excitation system, the generator terminal voltage rose and fell in near unison with the system bus voltage. A greater change of approximately 8% in generator terminal voltage is noted because it depicts the action of the var controller regulating reactive current in lieu of generator voltage.

Unlike the earlier test where the phase angle changed drastically with terminal voltage regulation, Fig. 7 illustrates the phase angle held essentially constant due to the regulated var and the regulated watt components. When the generator terminal voltage increased or decreased, the generator current decreased and increased respectively due to the turbine governor holding a constant load (MW) or torque and the var controller holding the reactive power at zero.

Fig. 7 shows the field characteristics relating to the var control mode. A close examination of these trends as compared to the field characteristics in Fig. 4 reveals an inverse relationship of field power between the two modes of regulation. This inverse characteristic exhibited in the var mode demonstrates the var controller's ability to decrease rotor heating when the system voltage is low, and pole slip when the system voltage is high.

Phase Angle Change	Generator Voltage	System Bus Voltage	Generator Current	Field Current	WATTS	MVA
0.15°	8.6%	9.02%	8%	11.7%	0	0

Table 2: Change for Generator Quantities in Var Regulation Mode

C. Power Factor Control

The last performance test involved placing the excitation system into power factor control. Here, the power angle is regulated by comparing the real power (watts) and the reactive power (vars). Final tests were limited to four transformer taps due to problems with the tap changer system. For clarity, the data in Table 3 compares the same tap settings using voltage, var, and power factor regulation. Figs. 8 and 9 graphically illustrate the data taken during the test.

The data in Table 3 illustrates that noted performance differences are again predominant between voltage regulation and power factor control.

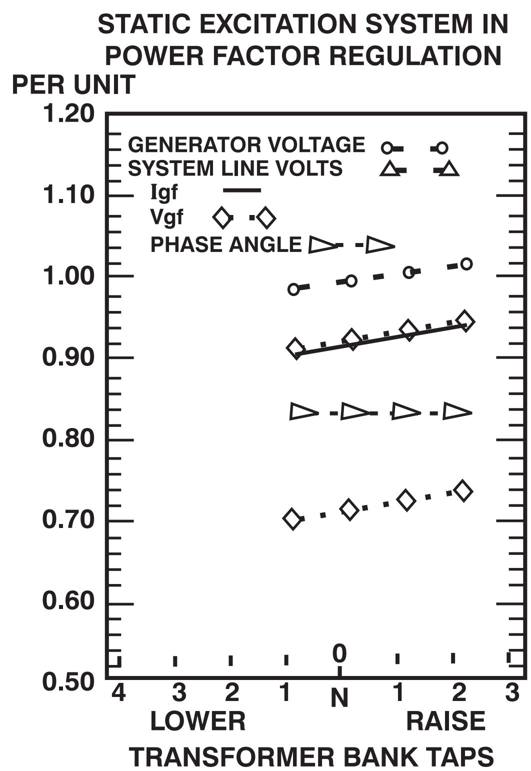

Fig. 8. Power Factor Control Minimum Phase Angle, Minimum Change

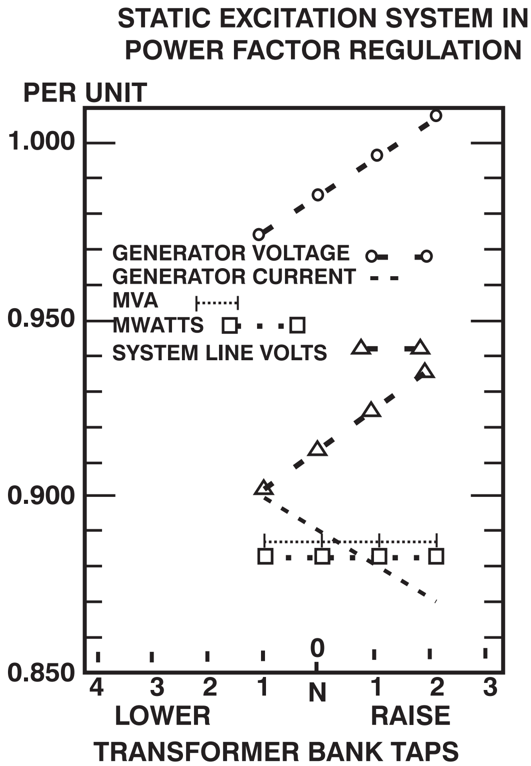

Fig. 9. Power Factor Control, Per Unit Change in Generator Voltage

Control Mode	Phase Angle Change	Generator Voltage	System Bus Voltage	Generator Current	Field Current	WATTS	MVA
VOLTAGE	7.9°	0.89%	2.5%	1.08%	10.6%	0	0.32%
VARS	0.1°	3.6%	3.73%	3.63%	4.67%	0	0
POWER FACTOR	0	3.3%	3.7%	3.3%	4.6%	0	0

Table 3. Voltage, Var Performance Comparison to Power Factor Regulation

In comparing power factor to var control, the data indicates nearly identical performance.

IV. OTHER FACTORS AFFECTING MACHINE PERFORMANCE

A. Brush Life for Synchronous Generators

For both old and new generators, where brushes are utilized, it is important that a machine's performance be optimized to insure long life at minimum maintenance The manner in which a generator is operated can influence the brush life and hence the related maintenance. Brushes are used to transfer the dc field current and voltage from either a rotating exciter or static exciter system to the rotor's collector rings. Brush selection is based upon a certain current density range where it can establish and maintain a satisfactory film important for lubrication. The lubrication helps ensure a good sliding surface between the brushes and the collector rings. If the current load is excessive, too much film may form, causing excessive brush decay and particle decomposition. This results in arcing, uneven heat distribution on the brush, and brush bounce. However, if the current density is too low, too little film will form, creating excessive friction over the collector ring. This again results in excessive brush wear, brush chatter, and actual brush breakage.

For those generators where voltage regulation control is utilized, it is not uncommon to see generator field excitation change extensively under extreme operating conditions. Data in Fig. 4 illustrate this phenomenon. For these systems under those conditions, brush life is expected to be shorter. Here a smaller machine would enjoy a maintenance advantage if equipped with a var or power factor controller.

B. Other Voltage Control Equipment

In large generator systems, voltage regulating units are desirable because they stabilize the system's terminal voltage. Smaller generators have little impact on changing the bus voltage, and in fact can lead to system coordination problems. These problems occur typically where capacitor and transformer banks are simultaneously used for voltage control.

In these systems where a small voltage regulated generator is utilized, nuisance switching may result between the voltage correcting equipment and the interconnected smaller generator that uses a terminal voltage regulator. These system disturbances are caused by excessive voltage correction from capacitor and/or transformer banks trying to compensate for the smaller generator's limited capacity to help keep system bus voltage constant. Secondly, it may cause unacceptable reactive current exchanges between the smaller generator and the utility bus depending upon the magnitude and direction of the voltage change.

For these systems, a compromise may be needed between both the voltage regulator and the Var/PF controller operation. During a system disturbance, the voltage regulator may need to provide voltage bus support and, after the event, return back to the Var/PF control set point. Today, with digital control, compromises can be resolved easily by adjusting gains within the excitation system to provide optimum control for either application. A high gain voltage regulator will provide fast transient response to improve the system voltage transient stability and help improve relay tripping coordination during a fault. After the system stabilizes, the Var/PF controller can maintain the Var or power factor set point without operator intervention.

V. CONCLUSION

The use of var/power factor controllers on generating units connected to the transmission system is not always desirable unless other considerations are made. In the case of a large system disturbance, the var/power factor controllers will degrade the system's ability to recover from low voltage conditions.

For large machine applications where constant vars are desired, but the advantages provided by a terminal voltage regulator are needed to provide voltage stability, additional provisions will be required for the var controller. For these applications, the var/power factor controller must be equipped with a slow integrated var function. In this case, the advantages of both a terminal voltage regulator and var/power factor operation can be achieved. During the initial disturbance, the voltage regulator will contribute to the voltage stability of the system, then after some time delay, the var control assumes command.

There are many factors affecting generator behavior when it is tied to a utility bus. System bus voltage fluctuation and area load distribution can cause small generators to become overloaded or possibly lose synchronizing torque unless limiters are utilized when the bus voltage changes from one extreme to another.

Data presented in this paper did not show the generator actually overloaded or extremely underexcited because of the controlled testing at the site. It did, however, show the tendency for a machine that is terminal voltage regulated to see larger field current swings when degradation of the bus voltage does occur.

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