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Excitation Control for High Side Voltage Regulation

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Abstract - Recent power system events have shown that voltage collapse can be a root cause of some widespread outages. The thrust of this paper is to discuss some means of mitigating system voltage depressions that are available through excitation control of high side voltage. While such control is usually available for individual units through reactive current control, it was difficult to arrange for this control in multi-unit plants where units share a common step-up transformer. Recent advances in the control architecture allow for such control to be easily implemented. The advantages of this control are outlined in this paper, together with some typical results to show expected benefits. Also, we will briefly review some related var control strategies for station and system voltage controls and describe their application.

Keywords - Excitation Controls, Generator Controls, var Regulation, Protective Limiters, System Stability, Voltage Stability.

1. Introduction

The primary function of the excitation system is to regulate generator voltage and thereby help control system voltage. Most commonly, utility generation is operated on voltage control while in many instances industrial and co-generation plants could be operated on var/pf control. An available feature in most excitation systems, that is not always considered, is reactive current compensation (RCC). The RCC allows for regulation of voltage at a different point than at the generator terminals. This is done by measurement of the terminal voltage and addition (or subtraction) of a voltage proportional to the line current.

By utilizing proper settings the RCC can be used to implement two different functions:

- Line Drop Compensation (LDC) that allows for regulating the voltage at a point part way into the step up transformer.
- Droop control that regulates a voltage internal to the machine, allowing units bussed together to share var loading.

The simultaneous use of LDC and droop, RCC functions, in multi-unit plants with common connection is easily designed into modern digital–based excitation systems

Proper use of RCC, including simultaneous use of LDC and droop where appropriate, offers an alternative to shunt capacitor compensation, with positive benefits of improved transient voltage support [1-2]. Some case studies on a small power system model are presented to illustrate and quantify the effects. A brief discussion of other options such as master station voltage control, and coordinated system volt/var controls is also presented

2. Var Support for System Stability

The issue of var support on the heavily loaded system can be as critical as the traditional measure of MW reserve margin [2]. Before discussing the options of improved var support from the generators, a brief review of the var support issue in general is warranted.

In general, the var losses that are required to be supplied are available from either rotating var's (generators and synchronous condensers), and/or various static var sources such as switched capacitors, SVC, STATCON, etc. The characteristics of these two types of var sources are different. Consider Fig. 1 which shows a system bus to which are connected a mix of static and rotating var sources. To make

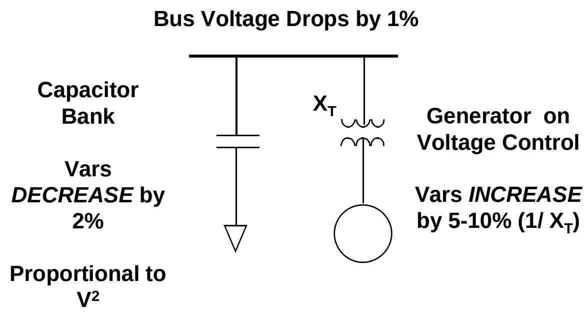

Fig. 1 - Comparison of Static and Rotating var Sources

the point, we consider the system bus voltage drops by 1% due to some external factor. Shunt connected capacitors will have their output reduced by 2% (of the bank nominal rating) since the output var's are proportional to the square of voltage. Inherently the static var source responds in the wrong way, reducing var output at a time when we would like to increase vars to support restoration of the system voltage. A rotating machine has an inherently beneficial characteristic to transiently supply vars during this same scenario. In the example shown the generator is connected to the grid through a step up transformer whose impedance is typically 10-20% on the generator MVA base. The same drop in system voltage of 1% results in an increase in vars from the generator of 5-10% of its rating. Further, the generator can increase var output through maintaining voltage control, up to the capability of the machine and transiently over and above the steady state capability within the overxcitation limits in a well designed excitation system

3. Reactive Current Compensation

For units which are in voltage control there is a function, normally a standard supplied feature, called Reactive Current Compensation (RCC) [3]. The RCC is a fast transient control that acts through the voltage regulator summing point. There is a slower acting control function that is discussed in the next section, called Master Station Voltage Control (MSVC). The RCC control provides for regulation of a voltage that is not the generator terminal voltage, but some other voltage synthesized using the terminal voltage, terminal current, and compensating impedance Z_C. The equation for the compensated voltage is defined in [4] as:

$$V_C = V_T + (R_C + jX_C)\, I_T$$

The voltage to be regulated is the compensated voltage, V_C, and it can be thought of as looking into the generator if the reactance X_C is positive (normally referred to as droop control) or looking outward into the network if X_C is negative (commonly referred to as line drop compensation). Normally, the resistive component, R_C, is neglected since the X/R ratio is high.

For a single generator connected to the system through a step-up transformer, line drop compensation (LDC) can be used to regulate the voltage at a point that is effectively somewhere in the middle of the step-up transformer. Typically, one might regulate to a point that is 50-80% of the way through the transformer towards the system high voltage bus. The closer one regulates to the HV bus requires the unit to provide more vars to support the HV bus. If the generator is small relative to the system connection and the net impedance after compensation is too low, the unit var swings may be excessive in response to system voltage changes. For a situation with an isolated unit, the LDC may provide a good way of having better transient regulation of either a plant or HV bus voltage.

4. Stability Impacts of RCC

To illustrate some of the issues relative to the effect of the RCC on stability, consider a simple 2-machine model. Generator 1 is connected through a step up transformer and an equivalent transmission line. The second generator is a larger equivalent machine representing the remaining part of the system. The transmission line has a reactance of Xe=40% while the step up transformer has a 10% reactance (on machine base). Fig. 2 shows the response of the generator terminal voltage and reactive power output to a three phase fault three quarters of the way down a transmission line (remote fault). The excitation system is set up with RCC in

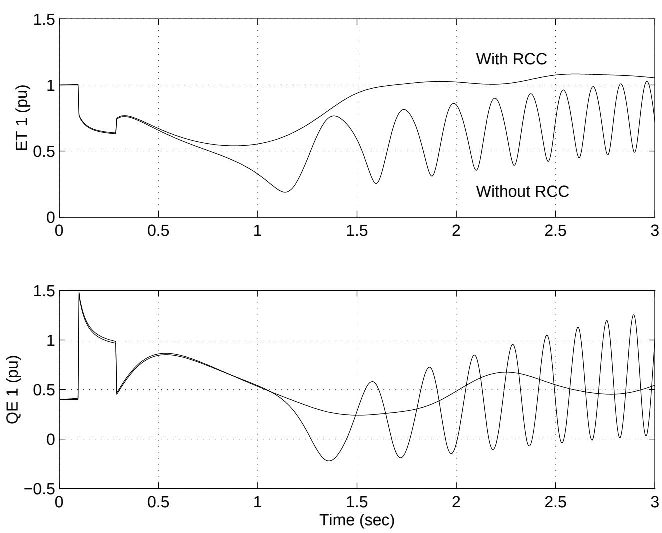

Fig. 2 - Comparison of Response to a System Three Phase Fault - With and Without RCC (LDC)

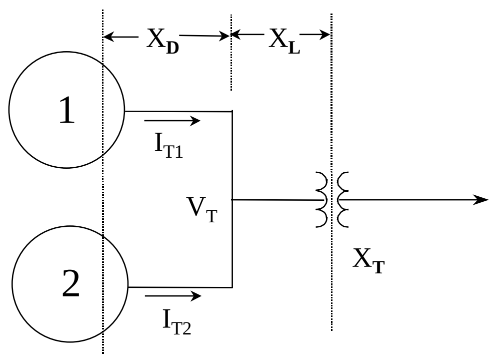

Fig. 3 - Two-Units Bussed Together, Showing Droop and LDC Compensation

LDC mode with compensation for 7.5% reactance looking into the system (75% compensation of the transformer impedance). The generator was loaded to 0.9 pu (rated) MW and 0.4 pu MVAR output, and the fault clearing time close to critical clearing time. The difference between stable response with the LDC and unstable response without the LDC (terminal voltage regulation only) is evident. In order to obtain maximum benefit from the exciter during transient events, a properly designed and operating OEL (Over Excitation Limiter) must be an integral feature of the exciter. The use of shunt capacitor compensation can provide similar benefit, but at consequent greater risk for reduction of stability limits for larger voltage reductions. The use of LDC can make a difference in those cases where the unit var output and consequent transient stability limits are of concern.

The other way of using RCC is to allow for var sharing between two or more units connected together on a common bus [3]. This is illustrated in Fig. 3, which shows two units connected together working through a step-up transformer. This configuration is common for either a cross compound (LP-HP) turbine generator combination, or hydro turbines sharing a split winding step up transformer connection. In this case it is required to have the RCC configured as droop control (positive value X_C – typically 5-6% on unit base) to regulate a voltage internal to the generator. This would provide an equivalent reactance to the common bus so that the units will share vars, as they would if there were a step-up transformer for each unit. In addition to droop, we can apply a simultaneous LDC control function to regulate into the step-up transformer (sometimes referred to as reactive differential compensation or cross-current compensation [7]). For each of the two units we can write an equation for the regulated voltage V_C which now depends on the current in both units.

$$V_{C1} = V_T + jX_{D1}I_{T1} - j(X_{D1}+X_{L1})(I_{T1}+I_{T2})$$

$$V_{C2} = V_T + jX_{D2}I_{T2} - j(X_{D2}+X_{L1})(I_{T1}+I_{T2})$$

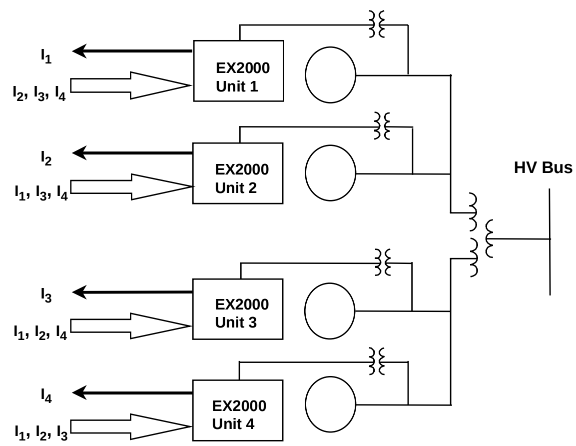

Fig. 4 – Four Unit Hydro Turbine Power Block, Showing Interconnection for HSVC

Where V_T and I_T are the terminal voltage and current, X_D is the droop impedance, and X_L is the line drop impedance. In theory the droop and line drop impedance's can be different on each unit so they are shown as subscript by unit number. It should be noted that each unit calculation requires the current from the adjacent unit(s). This concept can be extended to any number of units but typically the hydro turbine power blocks have 4 units, two one each side of a split winding connection. This is shown in Fig. 4 as a one-line diagram. In the past, it was required to actually wire CT circuits of adjacent units together, which involved considerable accommodation in the design and effort in wiring. The digital based excitation control system architecture [5] may allow easy access and transfer of the required information using low bandwidth signal connections.

The GE EX2000 excitation system, for example, can have the option for input of three additional current signals from adjacent units. In practice, the calculation in EX2000 is based on the use of vector math in the high-speed transducering algorithms to calculate the reactive component of current, in addition to the previous assumption of only using the reactance to calculate the voltage change. The advantage of using the reactive current is that only scalar quantities (magnitudes) have to be included in the calculations reducing the bandwidth requirements for the current signals. The net effect of these assumptions amounts to less than one percent error for normal values of Xc in the 5-10% range. This facilitates constructing the required algorithm for reactive compensation on up to four units that share a common step-up transformer connection. Each unit's excitation system uses the computed reactive current from its own unit, and the input reactive currents from the other three

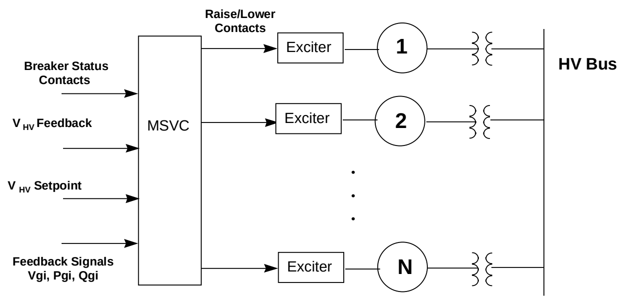

Fig. 5 - Overall Structure of MSVC Controls

excitation systems. The current signals are transferred using 4-20ma current loops, and equations similar to those shown previously for the two-unit case are easily implemented in software functions using reactive current in place of actual current.

5. Plant and System Volt/var Controls

The basic thrust of improving system stability margins is driving us towards ways of using volt/var control in a more coordinated fashion. The intent of these controls is to utilize the maximum range in var capability from the generators in a more automated fashion. The common factor of each of the systems reviewed here is that they require some input from adjacent units in a plant or in some cases all plants in the system. This kind of coordinated control requires a commitment and planning at system level and a participation from all the units, much in the same way as PSS application is used in all of the Western US to achieve good damping for intertie modes.

The first level of var control is what is called Master Station Voltage/Var Control (MSVC) [6]. This is a control function that monitors all the units in a power plant and provides adjustment to the individual excitation systems to insure that the volt/var for each unit is balanced in respect to its capability. A block diagram of the MSVC control is given in Fig. 5. The MSVC is a slower outer loop (controller not regulator) acting through the raise lower commands, similar to an individual unit var/pf controller. The MSVC can be configured in a number of ways, one possible way would be to measure the var output of the plant and use the MSVC to trim each excitation system to insure that each unit is providing a var output in proportion to its individual capability. In a station with different sized units and different impedance's for the step transformers, there might otherwise be a tendency for some units to have var swings larger than their share in proportion to the other units. Balancing the var loading will maximize the dynamic range of system var support from the station. It is recognized that the plant operators could do this same function, but the MSVC automates this process.

An extension of the concept of MSVC is a system that is applied to the Italian grid by ENEL [7]. This system is called REPORT and has the same basic interface in each plant as the MSVC control described earlier, that is, an adjustment of the excitation system voltage reference. Taking the coordination to the next level, they apply a system level controller that is then tied to each of the plants in the system. In this case the control center which has the system controller will supply the appropriate setpoint to each plant. This type of control coordination requires a commitment from the utility and most likely an investment in a control interface for each unit.

A related type of coordinated control has been adopted by Tokyo Electric Power (TEPCO) in their PSVR (Power System Voltage Regulator) [8]. In this system the control is also applied to all units as a modification to the voltage regulator to include a high voltage bus setpoint control loop, in addition to the normal generator voltage regulation. This system differs from the setpoint control concept in that it supplies a regulation loop to the voltage regulator which acts to insure that the HV grid voltage is regulated to a setpoint (with droop) to insure each unit is supplying its fair share of vars to support the HV bus voltage. In the TEPCO system all units have the PSVR control applied and the HV setpoint is varied with time during the day in patterns that are pre-selected and supplied by the system control center.

6. Summary and Conclusions

The use of reactive current compensation (RCC) for line drop compensation can provide stability improvements for a generator connected through a step up transformer. This type of control is often referred to as high side voltage control or secondary voltage control, as it offers tighter regulation of the high side voltage bus, by using more of the reactive capability of the units. In the case of multiple units bussed together, e.g. cross compound units or hydro turbine power blocks, the simultaneous use of both droop and line drop compensation can provide the same transient stability improvements. Studies of this control are recommended and may offer an alternative to other forms of reactive compensation for supporting system voltage.

The concept of Master Station Voltage Control (MSVC) and two notable system var controllers, the ENEL REPORT system and the TEPCO PSVR system, are mentioned to indicate what can be done by a utility which adopts a system wide control philosophy.

7. References

[1] P.G. Brown, et. al., “Economics of Switched Shunt Capacitors and Synchronous Condenser Kilovar Supply for Transmission Systems” AIEE Transactions – pt. IIIb, Vol. 73, February 1955, pp. 1553-9.

[2] C. W. Taylor, “Dynamic reactive Support in a Complex ac/dc Power System: Application on Western North American Interconnection/Pacific Intertie", IEEE Symposium on Application of Static Var Systems for System Dynamic Performance, 87TH0187-5-PWR.

[3] A.S. Rubenstein and W.W. Walkley, “Control of Reactive KVA with Modern Amplidyne Voltage Regulators”, AIEE Transactions PAS, December 1957.

[4] “IEEE Recommended Practice for Excitation System Model for Power System Stability Studies”, IEEE Standard 421.5 -1992.

[5] “Features Functions and Benefits of Digital Excitation Systems”, IEEE Task Force on Digital Controls, IEEE Trans. EC, Vol. 10, No 4, December 1995, pp. 706-713.

[6] W.J. Miller and H.H. Happ, “Voltage Scheduling and Control of Power Systems”, Proc. American Power Conference, 1985.

[7] V. Arcidiacono, S, Corsi, A. Natale, C, Raffelli, and V. Mendittio, “New Developments in the Application of ENEL Transmission System Voltage and Reactive Power Automatic Control”, CIGRE Paper 38/39-06, Aug./Sept. 1990 Session.

[8] S. Koishikawa, S. Ohsaka, M. Suzuki, T. Michigami and A, Akimoto, “Advanced Control of Reactive Power Supply Enhancing Voltage Stability of a Bulk Power Transmission System and a New Scheme of Monitor on Voltage Security”, CIGRE Paper 38/39-01, Aug./Sept. 1990 Session.

Biographies

Michael J. D’Antonio received his BSEE from Kansas State University in 1974 and his MSEE from Virginia Polytechnic Institute and State University (Virginia Tech) in 1982. He joined GE in 1975 and has worked in various technical and managerial positions and is presently Senior Application engineer for excitation system in GE's Industrial Control System business. Mr. D'Antonio has extensive experience in the design and application of microprocessor based controls system for power generation and has been issued 3 patents.

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Alexander Murdoch received his BSEE from Worcester Polytechnic Institute in 1970, and his MSEE and Ph.D. from Purdue University in 1972 and 1975, respectively. Since 1975 Dr. Murdoch has worked for General Electric, in the Power Systems Energy Consulting, where he is a consulting engineer. Since 1996 he has joined GE Drive Systems while still maintaining his role in PSEC. His areas of interest include rotating machine modeling, excitation system design and testing and advanced control theory. He is a member of the Excitation System Subcommittee in the IEEE.

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