MODELING AN ACTIVE POWER LINE CONDITIONER FOR COMPENSATION OF SWITCHING TRANSIENTS

Le Tang Mark F. McGranaghan

Electrotek Concepts, Inc.
408 North Cedar Bluff Road, Suite 500
Knoxville Tenseness, 37923-3605, USA

ABSTRACT

This paper describes an active power line conditioner using insulated gate bipolar transistors (IGBTs) to compensate for switching transients at sensitive loads. This technology is referred to in the paper as a voltage disturbance stabilizer (VDS). The operation principles and controls of the proposed VDS are presented and a detailed EMTP model of the VDS is described. The model is used to demonstrate the response of the VDS to typical capacitor switching transients which can be result from switching on the utility system. The rating requirements and operation limits of the device are identified and discussed.

1.0 INTRODUCTION

Capacitor bank switching is one of the most frequently performed switching operations in many utility systems. Energizing a capacitor bank on a transmission or distribution system can cause transient voltages within customer facilities that will cause misoperation or even failures of customer equipment. For some sensitive loads, such as adjustable speed drives, transient voltage magnitudes as low as 1.2 per unit can cause misoperation [1]. When the customer has power factor correction capacitors on the low voltage side of a distribution transformer, the problem can get worse because of the transient voltage magnification phenomenon [2,3].

The capacitor bank energizing transient can be controlled at the capacitor bank with preinsertion resistors or synchronous closing control. However, this can be an expensive proposition for large capacitor banks and it still may be difficult to limit the voltage at customer locations to very low values. Surge arresters at the customer location are not effective in limiting the transient to low enough levels for sensitive electronic equipment, such as adjustable speed drives.

In this paper, the authors describe an IGBT-based voltage disturbance stabilizer (VDS). Most capacitor switching transients seen at the customer voltage level have a dominant frequency between 300 Hz to 3000 Hz. These oscillations typically last a half to a couple of power frequency cycles [4]. In most cases, the amount of energy associated with the transients observed at customer facilities is not very high. The total energy associated with a major transmission or distribution capacitor bank switching is divided among many conducting circuit paths. As a result, the instantaneous disturbing power associated with these transients at each particular customer location is usually in the range of a few tenths to a couple of MW, which falls into the workable range of state-of-art IGBT based power line conditioning devices. For a successful VDS, energy storage capacity, proper controls, and fast response characteristics are essential.

An example VDS application is illustrated in Figure 1. The VDS is shunt-connected in parallel with the

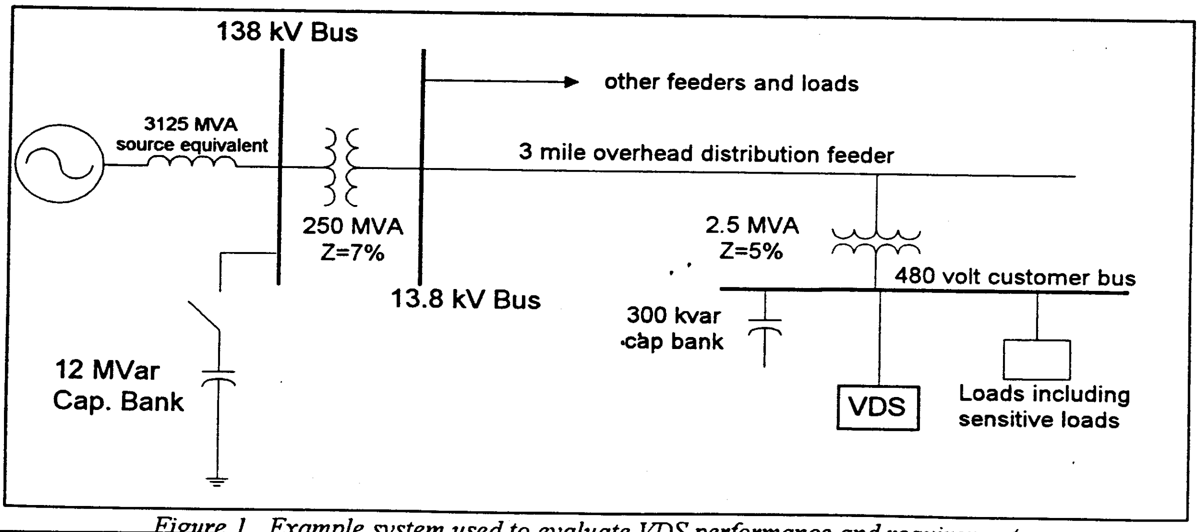

Figure 1 Example system used to evaluate VDS performance and requirements.

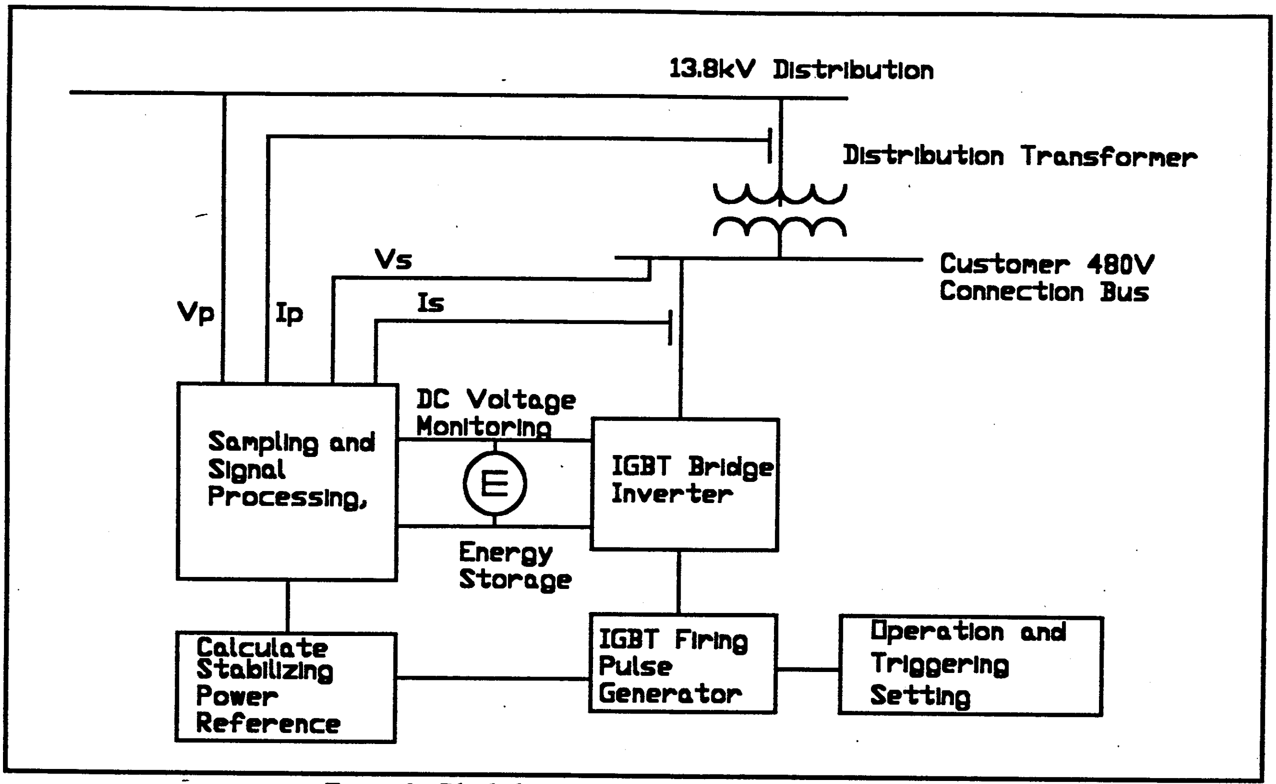

Figure 2. Block diagram illustrating VDS configuration.

sensitive load. It can provide full protection to the sensitive load from short-term supply voltage disturbances resulting from utility capacitor switching and other switching operations in the transmission or distribution system.

The proposed VDS consists of mainly an energy storage unit, an IGBT three-phase bridge inverter, and a DSP based signal processing and control block. A block diagram of the VDS configuration is shown in Figure 2.

In order to successfully stabilize a disturbance with dominant frequencies up to 3 kHz, the average switching frequency of the IGBTs needs to be 10 kHz to 60 kHz. The device would not be designed to provide any protection from a lightning strike or from a system disturbance with a dominant frequency exceeding 3 kHz because of limitations of applicable IGBT switching frequencies.

The individual functional blocks shown in Figure 2 are described in the following section.

2.0 VDS COMPONENTS AND EMTP MODELS

2.1 Energy Storage Unit

Real power injection is required to compensate for transient disturbances. This is different than the requirements for active filters that are only designed to compensate for steady state harmonics or reactive power. The stabilization energy needs to be stored before the disturbances in the energy storage unit. The energy storage can be realized using a superconducting magnet, fast discharging battery, supercapacitor, or an advanced flywheel system. For the described VDS configuration, the stored energy is in the form of a dc voltage source. This could represent any dc energy storage technology.

2.2 IGBT Voltage Source Inverter

The voltage source inverter is the heart of the VDS. This three-phase, full-wave inversion bridge is built using three identical IGBT inverter legs. A dc link neutral is established by equally dividing the dc voltage source capacitance between the positive and negative poles. This design allows the VDS to compensate for unbalanced system disturbances.

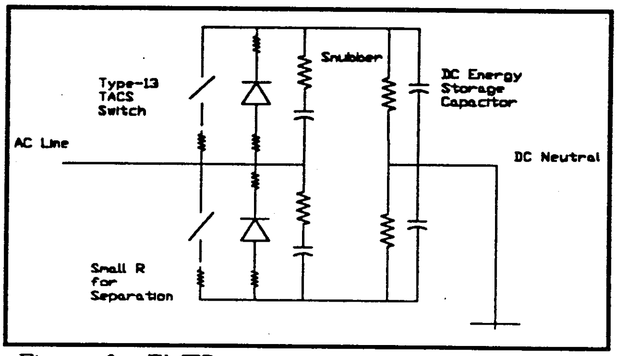

Figure 3. EMTP representation of one inverter leg.

Figure 3 illustrates the EMTP representation for one leg of the inverter. An anti-parallel diode and IGBT device form a switching cell in the physical design. They are represented in the EMTP model by a type-11 diode and a type-13 TACS controlled switch respectively.

It is worthwhile to mention the role of snubbers in the EMTP model. Physically, voltage snubbers are required solely to prevent the switching device from seeing an excessive rate of voltage change. However, the snubbers shown in this EMTP representation are also for controlling the numerical oscillation associated with the Trapezoidal solution method [5]. As a result, the parameters required for the snubbers in the EMTP model are dependent on the circuit being simulated and the step size selected for the solution. For this study, simple RC snubber circuits were used and they were sized to approximate the inverter bridge losses, while assuring the numerical stability of the simulations.

Because the VDS is designed to operate only for the short time duration of a system transient disturbance, the most important hardware limit for the switching devices is the thermal limit of the IGBTs. Some other constraints such as switching loss reduction, audible noise control, and EMF level limits are often imposed on other types of IGBT applications. These are secondary order considerations in the VDS application. Therefore, switching frequencies up to 60 kHz become feasible with the state-of-the-art IGBT devices for this application. For ratings in the MW range, series/parallel combinations of IGBTs will be necessary. However, for this example evaluation, a single device is used in each switching cell of the inverter leg as shown in Figure 3.

2.3 Operation Controls

In this parallel VDS configuration, the control of the VDS operation is accomplished by monitoring the voltage and current on the primary side of the distribution transformer. The concept of the compensation control is to generate gating signals for the voltage source inverter that will create a power injection to cancel the disturbing power of the transient. The result is a significantly reduced transient overvoltage magnitude on the low side of the distribution transformer, where the sensitive loads are connected.

Considering the capability of a digital signal processor (DSP) and the sampling resolution required to accurately characterize the power disturbance, a sampling rate of 532 samples per power frequency cycle is used in this EMTP demonstration. The discrete sampling is represented in the model by using a type-58 TACS device.

Input quantities to the control unit are three phase voltage and current signals. Output quantities from the control unit are a set of the current references which need to be injected into the system by the controlled action of the VDS voltage source inverter. A simplified signal processing flow chart is given in Figure 4.

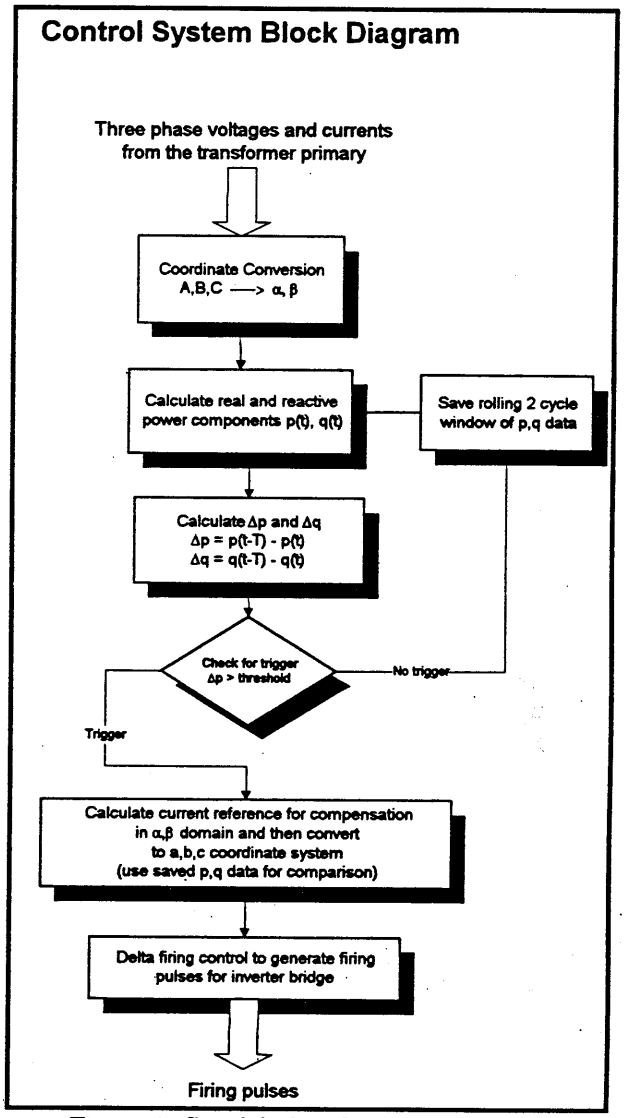

Figure 4. Simplified VDS control flow chart.

In order to calculate the phase current injection references, the sampled control input signals of phase voltage $V\{a,b,c\}$ and line current $I\{a,b,c\}$ are converted into the signals $V\{\alpha,\beta\}$ and $I\{\alpha,\beta\}$ in alpha-beta coordinates. The instantaneous powers p(t) and q(t) are calculated from the $V\{\alpha,\beta\}$ and $I\{\alpha,\beta\}$. Assuming that load conditions during the transient disturbance are constant, the calculated instantaneous power p(t) and q(t) contain constant components P(t) and Q(t) and fluctuation components $\Delta p(t)$ and $\Delta q(t)$. The constant components P(t) and Q(t) correspond to the active and reactive power demands of the loads for the steady-state operation prior to the system disturbance. The fluctuation components $\Delta p(t)$ and $\Delta q(t)$ correspond to the disturbing power associated with the transient disturbance. With a properly introduced time delay, disturbing power $\Delta p(t)$ and $\Delta q(t)$ can be separated from the total instantaneous power p(t)Δ and q(t). Then, the disturbing power Δp(t) and Δq(t) are used to derive the injection current references in two steps. First, the a-b domain injection current references are determined. Then, abc phase domain reference currents are obtained through α−β to a-b-c coordinate conversion. In the EMTP simulation, the above described signal processing is implemented using the EMTP TACS capability.

Ideally, if a perfect compensation is achieved, the customer low voltage bus should observe no transient at all during a system switching event. However, because of delays in the DSP and voltage source inverter responses, the protected sensitive loads will still see a transient, but with a greatly reduced magnitude and duration. In practice, perfect compensation is not necessary. The objective in only to control transient voltage disturbances to levels that will not cause problems with sensitive load equipment.

2.4 PWM Firing Pulse Generation

As in most PWM applications, the interval between two consecutive switching actions varies constantly within a power frequency cycle. A rigid definition of the switching frequency is not applicable. Thus, the concept of an average frequency is commonly used. In principle, increasing the inverter operating frequency helps to get a better compensating current waveform. However, there are device limitations. Control of the average frequency is realized by introducing a hysteresis characteristic into the PWM firing pulse generation logic as shown in Figure 5.

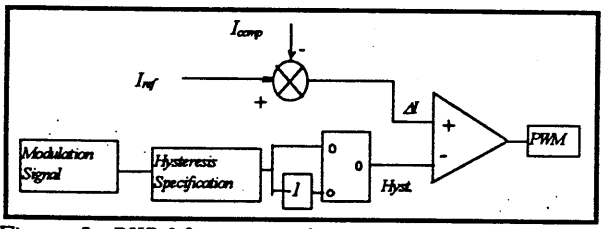

Figure 5. PWM firing signal generation with hysteresis characteristic.

In Figure 5, I_{ref} is the desired compensation current reference signal. I_{comp} is the actual inverter leg output current. An unmatched quantity ΔI is the current shaping error which is sent to the positive terminal of the comparing unit. The negative terminal of the comparing unit is connected to the output of a hysteresis characteristic generator.

When I_{ref} is greater than I_{comp}, the resultant ΔI is positive. If the magnitude of ΔI exceeds the upper boundary of a specified hysteresis band, the comparing unit output goes high, firing the upper bridge device of the leg and making the leg current increase. When I_{comp} becomes greater than I_{ref}, ΔI becomes negative. If the magnitude of the ΔI exceeds the lower boundary of the hysteresis band, the comparing unit goes low, firing the lower bridge device of the leg and making the leg current decrease. By increasing or decreasing the allowable current shaping error, which is determined by the bandwidth of the hysteresis characteristic, the average switching frequency can be controlled.

This firing algorithm is sometimes called a delta-modulation. In the simplest delta modulation control, an equal bandwidth over the whole power frequency cycle is used for the hysteresis. In this case, the modulation frequency is a constant. A nonlinear modulation can be used to help reduce the variations in the switching interval associated with a constant bandwidth.

2.5 VDS Triggering

The VDS is always on-line but is normally in an idle mode (unless it has a separate function to control steady state harmonics or reactive power). In the event of a transient disturbance, the VDS needs to be triggered as quickly as possible to control the transient and then blocked (or return to normal steady state compensation) immediately after the disturbance in order to be prepared for the next operation.

There are many different criteria which may be used for the VDS triggering. Because the active power disturbance is the main controlled quantity, setting an active power threshold for the VDS triggering is a logical choice. However, in some applications, this triggering method may cause problems. For example, for a load with a variable active power demand, setting a fixed power threshold can be difficult.

In this study, it was found that combining a disturbing power threshold and an active power flow directional sensing results in satisfactory triggering performance.

For any non-source type of load under normal operating conditions, the active power always flows from the system source to the loads. The power flow direction will only change during transient conditions. For example, when energizing a transmission or distribution capacitor bank, the uncharged capacitor draws its initial charging current from the system. If the customer has a capacitor bank installed, the customer capacitor will discharge energy into the bank being energized during this initial system capacitor bank charging. A similar situation occurs for induction machines within the customer facility. During the initial portion of the transient, the machine acts temporarily like a generator and deliveries power to the system.

In order to accurately calculate the disturbing active and reactive power Dp(t) and Dq(t) during the transient disturbance, a rolling recording and updating scheme is used to save samples of p(t) and q(t) for two power frequency cycles prior to the disturbance. During steady state operation, p(t) and q(t) are dc quantities. When the VDS is activated, the saved p(t) and q(t) samples for the previous two cycles are kept without updating. The updating of these reference signals is resumed after the system disturbance is fully decayed (Note that this assumed period of two cycles sets a maximum compensation period for transient disturbances that could easily be adjusted).

After the comparison reference updating (2 cycles) and if the energy storage unit recharging is completed, the VDS is ready for another disturbance. For different applications, different schemes for the VDS triggering and the comparison reference updating can be used.

3.0 SIMULATED VDS RESPONSE

Figure 6 illustrates a simulated transient voltage waveform at the 138 kV bus during energizing a 12 Mvar capacitor bank (see Figure 1). The waveforms in Figure 7 show the voltage at the 480V customer bus during this 138 kV capacitor energizing operation. The effect of the VDS is illustrated by the corresponding waveforms in Figure 8.

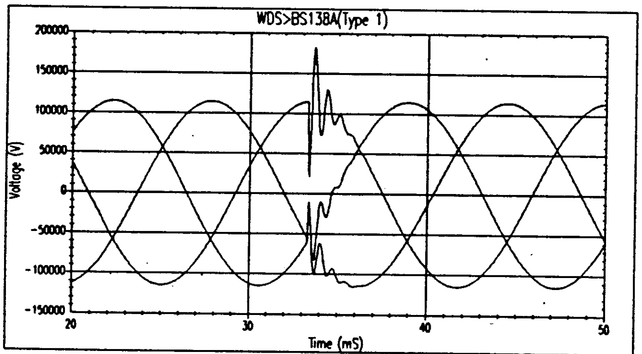

Figure 6. Voltage waveform at 138 kV bus during energizing of a 12 Mvar capacitor bank.

In the simulation, the VDS is triggered when a reversed real power flow is detected by the sampling and control block. and a 6.25% threshold of the disturbing active power Dp(t) is exceeded. The VDS is kept active until either a pre-set output energy level is reached or the detected power disturbance magnitude falls below a pre-set disturbing threshold. Figure 9 shows the calculated instantaneous power injection reference and the power actually injected by the VDS into the system in order to stabilize the customer bus voltage. In this particular example, the VDS only acted for about 2 ms for a given disturbing power index of 6.25%, defined by a ratio of the magnitude of the disturbing power Dp(t) and the magnitude of the steady-state power p(t).

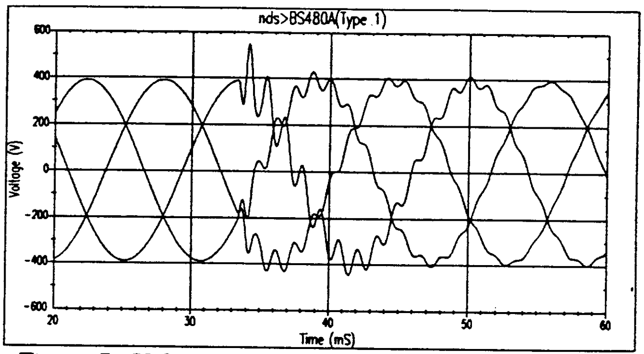

Figure 7. Voltage waveforms at customer low voltage bus during 138 kV capacitor energizing (without VDS)

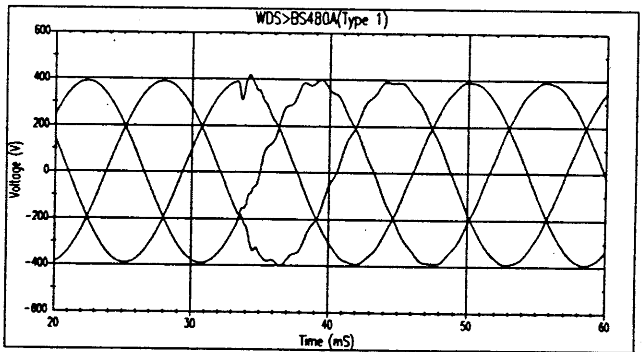

Figure 8. Voltage waveforms at customer low voltage bus during 138 kV capacitor energizing (with VDS).

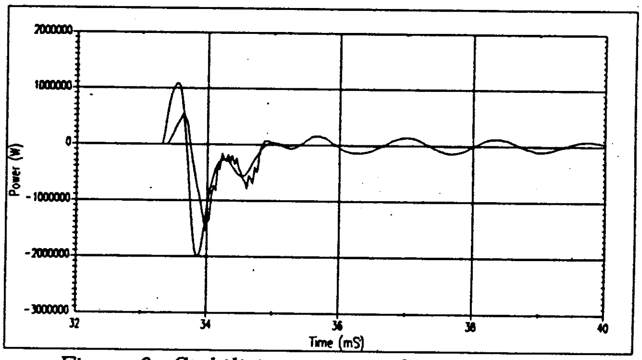

Figure 9. Stabilizing power reference and VDS injection for the voltage waveforms in Figure 8.

This EMTP simulation illustrates that the injection of the real power back into the distribution system greatly helped to control the customer bus overvoltage. It is interesting to note that, even though the injection power curve does not exactly match the stabilizing power reference as shown in Figure 9, the compensation of the transient is quite good.

The difference between the stabilizing power reference and VDS injection results mainly from the limit of the injection di/dt. The maximum rate of change for the injection current is determined by the equivalent inductance between the system source and the VDS and by the available driving voltage across this equivalent inductance.

In general, to improve the VDS performance, one can either reduce the size of the equivalent inductance or raise the dc link voltage of the VDS. However, as shown in Figure 9, it is not necessary to achieve an ideal compensation in order to limit the transient disturbance to acceptable levels at the low voltage bus.

In Figure 10, the corresponding phase-a voltage waveforms at the 13.8 kV side of the 2.5 MVA distribution transformer, with and without the VDS, are given. These waveforms are practically identical. The VDS controls the transient at the customer bus without affecting the system transient on the 13.8 kV side. This shows that the effects of the VDS can be localized without interfering with the rest of the distribution system.

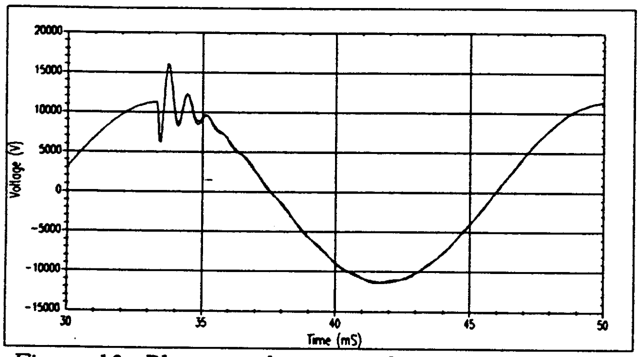

Figure 10. Phase-a voltage waveforms at 13.8 kV with and without VDS compensation during capacitor energizing at the 138 kV bus.

The inverter configuration used for the VDS is the same configuration used for many other power conditioning applications. For instance, inverters for energy storage technologies that can provide ride through during voltage sags and interruptions use the same configuration. Inverters for active harmonic and power factor compensation also use the same configuration. The proposed transient disturbance compensation can be implemented with the same hardware with only control system modifications.

4.0 CONCLUSIONS

- An inverter configuration using fast switching IGBTs and an energy storage element (a voltage disturbance stabilizer - VDS) can be configured to compensate for transient overvoltages affecting sensitive loads within customer facilities.
- Ideal compensation is not necessary to control transients caused by switching events, such as capacitor energizing, to acceptable levels for very sensitive loads, such as adjustable speed drives.
- The control technology proposed for the VDS can be implemented along with other controls for steady state compensation of harmonics and reactive power or for ride through support during voltage sags and interruptions.
- The EMTP can be used to model the VDS hardware and controls. The VDS can then be evaluated in actual field applications without expensive prototyping and field tests.

5.0 REFERENCES

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Le Tang was born in Beijing, China. He received his BS degree in Electrical Engineering in 1982 from Xi'an Jiaotong University, Xi'an, China, his MEng. and Ph.D in Electric Power Engineering from Rensselaer Polytechnic Institute in 1985 and 1988 respectively. Dr. Tang conducts harmonics, transients and other power quality related analyses and studies. He is actively involved in renewable energy development and application, including wind electric power generation and its interface with electric utility systems.

Mark McGranaghan received his BSEE and MSEE degrees from the University of Toledo. He has been involved in a wide range of activities dealing with concerns for power quality and the integration of power electronic equipment on the power system. He has developed and taught harmonics, transients, and power quality seminars during the past 10 years, and has been actively involved in rewriting the IEEE Harmonics Standard (519-1981).