VOLTAGE SUPPORT TRANSFORMER A NOVEL DEVICE FOR IMPROVED POWER QUALITY

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ABSTRACT

This paper describes an innovative device Voltage Support Transformer (VST) for improved power quality during power system transients. The VST applications that reduce voltage sags caused by faults in power systems and reduce overvoltages caused by shunt capacitor bank switching are presented.

Voltage sags (dips) are caused by short circuits on either the utility transmission or distribution system. Duration of voltage sags depend on the fault types. Whenever a fault occurs in the power system that causes voltage sag at the fault location it will also cause voltage sag at loads that are connected to the nearby feeders. Unfortunately, even if an industrial facility with a sensitive manufacturing process is not connected on the faulted circuit, voltage sags may affect the manufacturing process. When installed at the utility substations that provide power for an industrial facility, the VST will support the system voltage for the whole facility.

Shunt capacitor bank switching may cause high overvoltages that can endanger normal operation of sensitive load and, in some cases, cause high overvoltages that may damage power transformer insulation. The VST may effectively reduce the capacitor bank switching overvoltages.

The VST is a specially designed single-phase transformer that mutually couples the same phases of two or more lines and is connected in series with the loads. It uses a change in current from one line in which a fault condition or other power perturbation exists to create a voltage change in one or more of the other lines of the network connected to the same bus, to maintain or support the voltage in those lines at or near pre-perturbation levels.

INTRODUCTION

Voltage sags (Figure 1) are recognized as one of the major undesirable problems for manufacturing processes. Article [1] states “Voltage sags are one of the most expensive power quality phenomena in industry. The economic impacts of voltage sags can be quite large”... Whenever a fault occurs on a power system that causes a voltage sag at the fault location, it will also cause a voltage sag at loads that are connected to the nearby feeders. Unfortunately, even if an industrial facility having sensitive manufacturing process equipment is not connected on the faulted circuit, voltage sags may affect a whole manufacturing process. Voltage sags occur whenever a short circuit occurs on either the utility transmission or distribution system. The time duration of voltage sags relates to the character of faults, temporary or permanent. If a fault is temporary, the voltage sag lasts until a protective device operates and interrupts the fault. If a fault is permanent, the voltage sag duration will be longer since the protective device may reclose one or more times while attempting to re-energize the feeder, causing a voltage sag every time when attempting to re-energize the feeder.

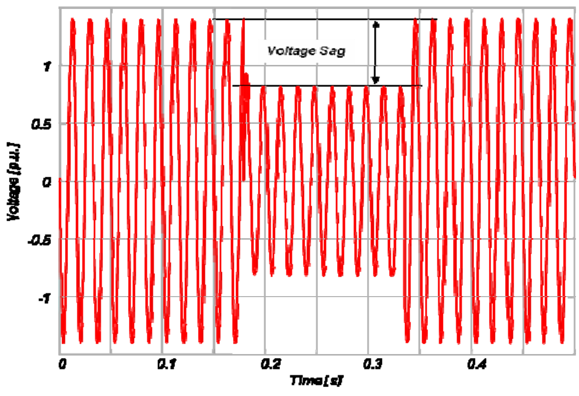

Figure 1 Voltage Sag (Dip)

Studies [2] indicate that voltage sags cause 90% of transmission-related power quality problems and that the typical electric utility customer experiences 30 to 50 voltage sags per year. The number of total power interruptions per year is much smaller than the number of voltage sag occurrences. The majority of voltage sags are caused by single-phase faults. Three-phase voltage sags represent only about 15% of all types of voltage sags. The cause of most voltage sags is a short-circuit fault occurring either within the industrial facility or on the utility system. Starting large motors also causes voltage sags. The extent of voltage sags depend on the fault impedance and source impedance.

Energizing a shunt capacitor from a predominately inductive source results in an oscillatory transient voltage at the capacitor bus with a magnitude that can approach twice the peak rated system voltage when energizing at the voltage peak (Figure 2). The closer to zero voltage at which a capacitor is energized, the lower the resulting transients.

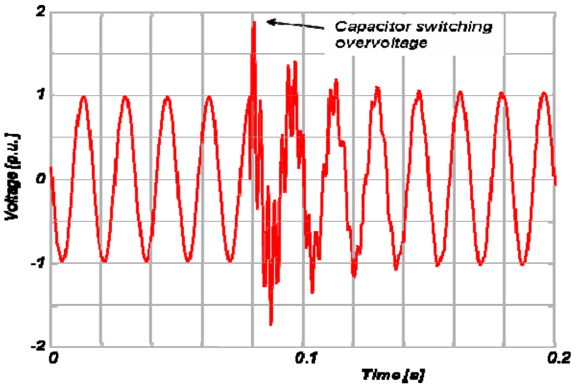

Figure 2 Capacitor Switching Overvoltages

The voltage tolerance envelope published by Technical Committee 3 (TC3) of the Information Technology Industry Council indicates the magnitude and duration of undesired events. Voltage magnitudes below the curve may cause the load to drop out if an power outage exceeds 20 ms, while voltage magnitudes above the curve can cause other equipment malfunctions, such as insulation damage, over voltage trip or over excitation. However, field tests conducted on an electrical distribution system in a residential area in Florida, USA confirmed that also short power interruptions of only 12 ms to 15 ms may have negative impact on the load even though these power interruptions are shorter than specified by the ITI curve. These tests were performed with a goal to determine the relative effects of expulsion fuse and current-limiting fuse operations on power quality [3].

VOLTAGE SUPPORT TRANSFORMER

The main characteristics of the Voltage Support Transformer (VST) include:

Multiple performances. The VST reduces voltage sags and mitigates capacitor switching overvoltages, harmonics, and other disturbances caused by current change in the power network. Since it uses the fault current for energy it can operate multiple times and in rapid succession, since no recharge time is needed.

Applicable in transmission, distribution and low-voltage systems. The VST can be designed for any voltage level and will effectively support voltage at every voltage level.

Supports voltage at bus and adjacent feeders. Whenever an overcurrent fault occurs that causes voltage sags on non-faulted lines, the VST instantaneously supports the voltage on non-faulted lines providing constant voltage during the fault. The VST may be designed to support 100% voltage sags for the whole duration until the protective device in the faulted feeder operates and disconnects the faulted feeder. The same statement applies for mitigating overvoltages during capacitor switching.

Fault current limiting. The VST prevents voltage sags and interruptions caused by voltage sags while reducing fault current magnitudes during fault conditions. In this way, power equipment is less stressed during overcurrent faults. Therefore, power distribution systems may be constructed less expensively than without VST.

Works for all faults. The VST provides voltage support for all overcurrent fault types such as single-phase-to-ground, phase-to-phase, phase-to-phase-to-ground, and three-phase faults.

Works for entire duration of fault. The VST uses energy from the power perturbation in the faulted feeder, so it does not require an energy storage device.

Easy to maintain. The VST is maintenance free and has no moving parts.

Reliable device. The VST is designed on proven transformer technology. There are no power electronic elements.

Low cost device. The VST can be manufactured less expensively than power electronic devices intended for the same purpose.

Principle of Operation

The VST is a specially designed single-phase transformer that mutually couples the same phases of two or more lines. It uses a change in current from one line in which a fault condition or other power perturbation exists to create a voltage change in one or more of the other lines of the network connected to the same bus, to maintain or support the voltage in those lines at or near pre-perturbation levels.

The VST is connected in series with loads. The VST is designed mainly for installation in substations, although it may also be installed downline from a substation. Figure 4 illustrates a single-line diagram of a distribution system with two lines (feeders). VST 1 and VST 2 are connected in each phase in series with Load 1 or Load 2 through Line 1 or Line 2, respectively. Circuit breakers CB 1 and CB 2 are connected in series with the VST windings. To demonstrate efficiency of the VST in supporting the system voltage, identical fault events without and with the VST were compared.

Fault Event without VST. The first assumption is that no VST is installed between Lines 1 and 2 as shown in Figure 3. If a fault condition occurs on one line, for example, an overcurrent condition on Line 1, fault current would flow through source impedance Zs and through Line 1 to the fault location. This overcurrent in Line 1 would cause a voltage drop (dV) in the source impedance Zs which would cause a voltage reduction on Line 2, and the Load 2 will experience voltage reduction (voltage sag), even though no fault exists on Line 2. Stated differently, an overcurrent in Line 1 will adversely affect the voltage and current being supplied to the load on non-faulted Line 2.

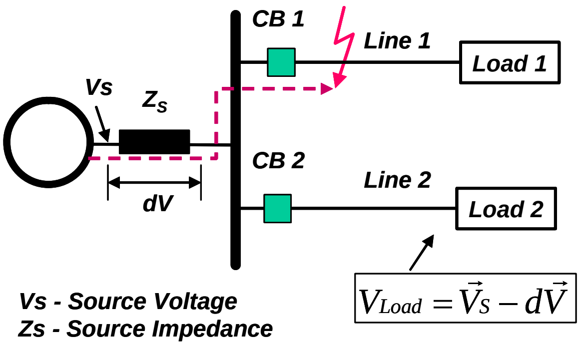

Figure 3 Fault Event without the VST

Fault Event with VST. For the same fault conditions VST 1 will support the voltage for Load 2 (Figure 4). Let us assume a single-phase-to-ground fault on Line 1. Fault current will flow through source impedance Zs, through Line 1, and through VST 1, which is connected in series with Line 1. Overcurrent which flows through VST 1 will induce a support voltage (dV) in VST 2, which is connected in series with Line 2 as shown in Figure 4. This induced voltage will maintain and support the voltage and current to Load 2 at or near pre-fault condition levels. Accordingly, Load 2 will experience substantially unchanged voltage and current during the fault. At the same time, the fault current magnitudes on Line 1 will be reduced by the VST's own intrinsic impedance during the fault condition.

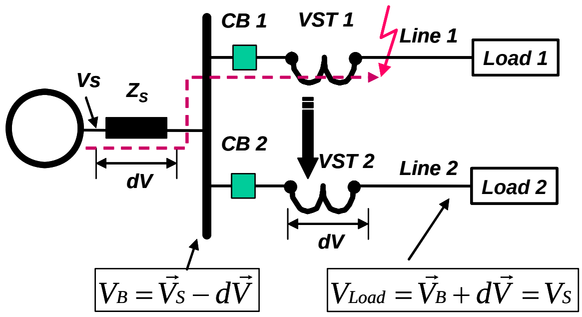

Figure 4 Fault Event with the VST

APPLICATIONS

Voltage Support Transformers can be installed in many different ways depending on location and number of lines to be protected. In applications with only two lines, two different VST installations are feasible. One VST per phase for both lines [5] and [6], or one VST per phase for each line as shown in Figure 4. Figure 5 illustrates an application of four VSTs to support voltages in all four lines (feeders). VST 1 simultaneously supports voltages in Line 2, Line 3, and Line 4 for faults on Line 1. VST 2 simultaneously supports voltages in Line 1, Line 3, and Line 4 for faults on Line 2. The same principle applies for VST 3 and VST 4.

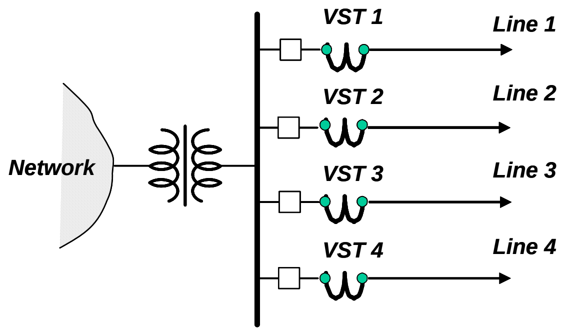

Figure 5 The VST Application in Substation to Protect all Four Power Lines

<u>Voltage Support during Faults in Power Network</u>

As mentioned in the previous text, the cause of most voltage sags is a short-circuit fault occurring either within the industrial facility or on the utility system. The VST supports system voltages during faults on any feeder connected to the same bus. To investigate the effectiveness in supporting the system voltages, high power tests were performed using a full size VST. Figure 6 shows high power test results verifying effectiveness of the VST in supporting the system voltage during faults on Feeder 1. For a fault causing a 50% voltage sag, the VST supports the voltage at Feeder 2, maintaining the load voltage at 1 p.u. Without the VST, voltage sag at the load would be 50%. In addition, the VST also reduced voltage sag at the bus to only 14%. Without the VST, voltage sag at the bus would also be 50%.

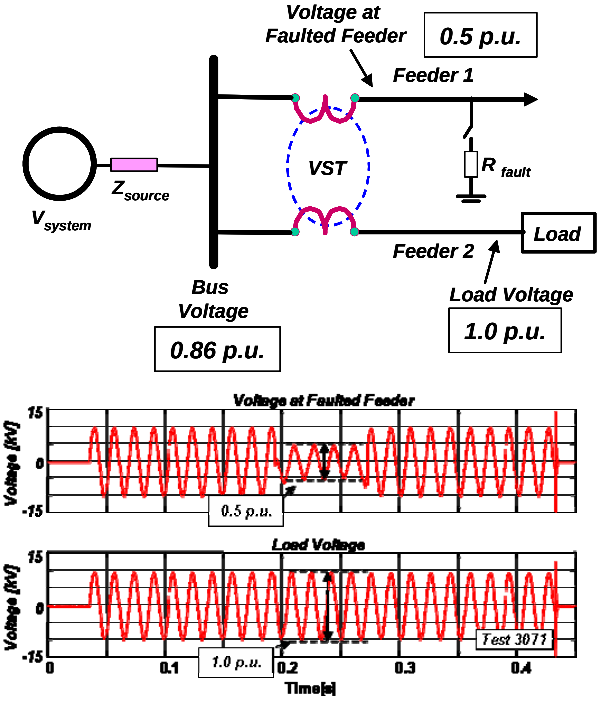

Figure 6 Effectiveness of the VST in Supporting the Load Voltage during Faults on Nearby Feeders, (a)-test setup, (b)- high power test results

Mitigation of Capacitor Switching Overvoltages

Energizing a shunt capacitor from a predominately inductive source results in an oscillatory transient voltage at the capacitor bus with a magnitude that can approach twice the peak rated system voltage when energizing at the voltage peak. The closer to zero voltage at which a capacitor is energized, the lower the resulting transients. Over voltage mitigation techniques may include pre-insertion resistors, and synchronous closing of each phase near a voltage zero. An alternative method is to use the VST.

Figure 7 shows high power test setup and test results verifying effectiveness of the VST in mitigating capacitor switching overvoltages. Energizing the shunt capacitor bank caused 1.8 p.u. overvoltages at the capacitor side of the VST. However, the VST entirely mitigated overvoltages at the protected load maintaining the voltage at 1 p.u. In addition, overvoltages at the bus are also reduced to 1.16 p.u.

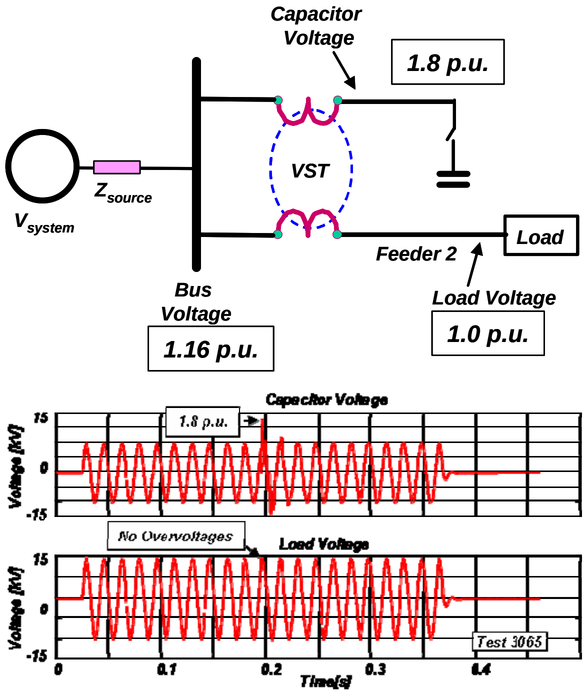

Figure 7 Effectiveness of the VST in Mitigation Capacitor Switching Overvoltages, (a)-test setup, (b)- high power test results

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