Protect distribution substation capacitor banks at low cost


Economical voltage sensor and solid state relay circuitry team up to trip ailing capacitor banks

A substation capacitor bank protection application usually involves a number of complementary protection schemes. Short-circuit protection for the individual capacitor units is furnished by fuses that clear internal faults, minimizing the probability of capacitor case ruptures. Short-circuit protection for the bank and the system against major bank failures may be provided with power fuses or, where fault levels are exceptionally high, with circuit breakers and associated relaying.

In addition to these protective techniques, unbalance relaying is now widely employed on large, expensive substation banks to provide protection for individual capacitor units against cascading overvoltages initiated by loss of capacitor units in the same series group. Historically, capacitor bank unbalance protection has not been affordable for smaller, less expensive distribution-substation capacitor banks.

However, with the recent introduction of a low-cost protection package, it is now advisable to consider unbalance protection for smaller capacitor banks.

Overvoltage: the bane of capacitor banks

Figure 1 diagrams a single ungrounded wye bank with overcurrent protection provided by fuses on the individual capacitor units. Proper sizing of the capacitor unit fuses will minimize the probability of case rupture when internal faults occur.

A fault in a capacitor unit, such as at X, results in blowing of the unit’s fuse. This open condition increases the impedance of that series group, thereby raising the voltage across the remaining capacitors in that faulted group. Removing successive capacitor units in a given series group results in an ever increasing voltage across the remaining units in that group.

In the early stages, when the overvoltage is less than 1.1 pu, the remaining capacitor units do not suffer significant life reduction. When the overvoltage exceeds 1.1 pu, capacitor unit life is shortened dramatically because of the compounding of the overvoltage stress on the remaining units. This phenomenon - which is termed cascading overvoltage - results in the accelerated failure of capacitor units, leading to the eventual removal of the entire series group.

Attendant with the failure of capacitor units is the risk of case rupture. Case rupture of capacitors insulated with polychlorinated biphenyls (PCBs) can cause contamination of the surrounding area and equipment. Case rupture of capacitors insulated with non-PCB dielectrics may result in a fire. In that any spill is highly undesirable, a major objective in the operation of capacitor banks is to detect the loss of individual
capacitor units and communicate that information to operating personnel who can investigate for a possible spill.

**Protect from cascading overvoltages**

Wisconsin Electric Power Co. is installing capacitor bank unbalance protection schemes on all of its substation capacitor banks to guard against cascading overvoltages and to detect the loss of individual capacitor units. The larger and more critical of the transmission substation and the distribution substation banks are protected by the S&C Type UP Automatic Control Device, a highly sophisticated control designed expressly for application on ungrounded wye-connected shunt capacitor banks. This proven solid-state device, manufactured by S&C Electric Co., Chicago, monitors the capacitor bank neutral voltage, measured by a neutral-to-ground connected S&C Potential Device, to detect losses of individual capacitor units. Individual alarm and tripping functions are provided to notify operating personnel of a minor bank unbalance and to trip the bank for severe unbalance. Wisconsin Electric uses the alarm function to detect the loss of a single capacitor unit at which time the overvoltage is still less than 1.1 pu on the remaining capacitor units in the group. This alarm is communicated to Wisconsin Electric’s System Control Center from which trouble personnel are dispatched to check for capacitor unit fuse operation. The bank is tripped off the system when enough individual units have been lost to cause the voltage on the remaining units to exceed 1.1 pu.

The UP device offers discriminating sensitivity to overvoltage stresses on individual capacitor units within the capacitor bank, while remaining insensitive to routine system and back-to-back switching disturbances. A unique feature of the control provides a simple method of compensation for capacitor bank signal errors introduced by capacitor unit manufacturing tolerance variations and by system voltage unbalance.

**Tailor protection to smaller banks**

Many of Wisconsin Electric’s distribution substation capacitor banks do not require the UP’s combination of individual alarm and tripping functions since loss of a single capacitor unit results in sufficient overvoltage to make tripping advisable. Additionally, the economics of these small distribution substation capacitor banks do not justify applying the sophisticated UP device and associated potential device.

Typically, these banks are in small, remote, unattended distribution substations. They range in size from 1800 to 4800 kVAR and are configured as ungrounded wye-connected banks. The banks operate at a nominal system voltage of 26.4 kV. Capacitor units are individually protected by ANSI K-Speed fuse links and banks are fused with SMD-20 standard or slow-speed power fuses (Fig. 2). Individual capacitor unit fuses are applied at the lowest possible fusing ratio that will provide maximum protection against case ruptures without incurring nuisance fuse operation due to switching or current surges. As mentioned previously, however, individual capacitor unit protection does not totally eliminate the risk of capacitor unit case rupture.

These substations are inspected about once every two to three weeks, at which time capacitor banks are checked for blown capacitor fuses and other abnormalities. Without an automatic protection scheme, PCB contamination or non-PCB related fires could occur and go undetected. Wisconsin Electric considers any delay in detection of these conditions unacceptable.

**Retrofit: cost effective solution to operating problem**

A review of the economics of the operating problem suggested that the most cost effective solution would be to retrofit the capacitor banks with a control scheme. The scheme would both...

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*Fig. 1. In a simple ungrounded wye capacitor bank, loss of a capacitor unit at X causes overvoltage on remaining units in that group.*

*Fig. 2. Wisconsin Electric Power Co.'s distribution substation capacitor banks are configured as ungrounded wye-connected banks with one series group per phase and four to eight parallel connected capacitor units per group, depending upon bank size. Capacitor units are individually fused and banks are protected with one fuse per phase.*
automatically remove a bank from service upon the failure of a single capacitor unit - thus guarding against compounding of failures; and simultaneously send an alarm to Wisconsin Electric’s System Control Center over existing communications links - so that operating personnel could be dispatched immediately to take appropriate action at the unattended substation.

The search for a low cost scheme that would provide the required protection and alarm led to trial installations of a unique protection scheme developed in collaboration with S&C Electric Co. The scheme was implemented with an economical voltage sensor, the S&C Outdoor Voltage Sensor, and a simple solid-state relay, the S&C Type LUC Bankguard™ Relay. In principle, the scheme operates like the sophisticated Type UP Automatic Control Device, but it provides only a trip function (with trip indication), and it is not designed to provide compensation for inherent system or capacitor bank unbalance.

**Watches over unattended banks**

Three trial installations were made. One on the 2400 kVAR capacitor bank at Salem Substation is pictured in Fig. 3 and diagramed in Fig. 4. The neutral-to-ground voltage is monitored by the Outdoor Voltage Sensor and supplied to the Bankguard Relay in the form of a low voltage signal.

This signal is first passed through the Bankguard’s isolation transformer, a high impedance buffer amplifier to minimize loading of the voltage sensor, and a bandpass filter to eliminate the effects of harmonics which may be present at the capacitor bank neutral. The signal is then compared to the preselected (field adjustable) lockout level setting. If the voltage signal exceeds the relay’s lockout level setting, a built-in electronic timer is activated. The timer, which is also field adjustable, is set to allow time for individual capacitor unit fuses to respond to evolving faults within the units, thereby permitting visual identification of the capacitor units in need for replacement. After the timer has completed its cycle, a latching type output relay supplies an opening signal to the three pole switch, effecting isolation and lockout of the capacitor bank. An isolated latching contact on the output relay provides for remote alarm over communication links to Wisconsin Electric’s System Control Center.

**The question of error voltage**

A residual voltage is always present between the capacitor bank neutral and ground because of inherent capacitor bank unbalance resulting from manufacturing tolerance variations.
among capacitor unit; in the bank and because of system voltage unbalance. This "error" voltage is superimposed upon the neutral-to-ground incremental voltage that appears as the result of isolation of individual capacitor units.

The error voltage and the neutral-to-ground incremental voltage resulting from loss of each capacitor unit are phasor voltages that have both magnitudes and associated phase angles. The error voltage could be additive with respect to the neutral-to-ground voltage resulting from isolation of capacitor units in one phase leg and subtractive with respect to the neutral-to-ground voltage resulting from isolation of capacitor units in another phase leg. Since it was not possible to predict how the voltages would combine under all failure modes, Wisconsin Electric engineers carefully weighed the need for error voltage unbalance compensation in the protection scheme that was developed expressly for the smaller capacitor banks.

**Unbalance compensation not needed**

As a rule, a capacitor bank protection scheme should provide for error voltage unbalance compensation if the magnitude of error voltage approaches 50% of the neutral-to-ground incremental voltage that occurs as each capacitor unit is isolated from the bank. But engineering judgment led Wisconsin Electric engineers to believe that any error voltage in the relatively small capacitor banks under consideration would be negligible. Additionally, Wisconsin Electric's 26.4 kV system serves predominantly balanced three phase loads. Therefore, consensus was that the added cost for designed-in unbalance compensation was not justified. Large capacitor unit kVAR sizes were judiciously selected when configuring the banks to assure that the incremental neutral voltage developed by the loss of one unit would be substantial.

**Test results excellent**

To prove that the Bankgard relay would perform as expected without unbalance compensation, the three trial installations were monitored over a 12-month period. In repeated tests, bank error voltages were compared with capacitor bank neutral-to-ground voltage increments resulting from isolation of one capacitor unit by removal of its fuse. This comparison showed that error voltages averaged less than 15% and were never more than 35% of the incremental neutral-to-ground voltage for an unbalanced bank. The Salem Substation capacitor bank experienced three separate capacitor unit fuse operations after installation of the Bankgard relay protection scheme. On all three occasions the capacitor bank was successfully switched from the distribution system and a remote alarm supplied to Wisconsin Electric's System Control Center upon isolation of a capacitor unit by fuse operation.

The trial installations have established the reliability of the protection scheme: the Bankgard relays have performed as intended—without failures of the relays to operate when they should and no false trips.

Consideration is now being given to using the Outdoor Voltage Sensor (25 kV rating) and the Bankgard relay on 9600 kVAR banks on Wisconsin Electric's 34.5 kV system. The application of the Bankgard Relay, with a suitable voltage sensing device, on 69 kV capacitor banks is also under study.

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