

KILOVAR BRIEFS

FROM THE COOPER POWER SYSTEMS' CAPACITOR PLANT

July 1993

GREENWOOD, SOUTH CAROLINA

Issue 22

When is a Compensating Unbalance Scheme Necessary?

Most substation capacitor banks are protected with an unbalance relay scheme. The purpose of such schemes is to detect the steady state overvoltage that occur within a capacitor bank when one or more fuses protecting the capacitors have operated. These schemes operate by detecting the effect that the different impedances of the three phases of the bank exhibit after fuse operations. However, phase-to-phase voltage unbalances can also cause unbalance-like conditions in a balanced bank. Some unbalance relay schemes are able to compensate for any system phase-to-phase voltage unbalance that may exist, others can not. The question this issue of the KiloVar Briefs addresses is when is it important to use the more expensive compensating unbalance relay schemes.

Compensating and Non-compensating Unbalance Relay Schemes

By compensating, we mean an unbalance scheme which is able to differentiate between capacitor bank unbalance due to causes within the capacitor bank and those causes external to the capacitor bank. This is most easily seen in the following two schemes.

The first bank, shown in Figure 1a, is a single series group, grounded wye capacitor bank with a CT between neutral and ground. Note that when all capacitors are in service the bank is what we refer to as being balanced; that is, the currents in the three phases of the bank are equal in magnitude, and 120° out of phase with each other. Therefore the three currents sum to zero at the bank's neutral, resulting in no current flow to ground.¹ When a fuse operates, the impedance of that phase changes, the currents are no longer equal,

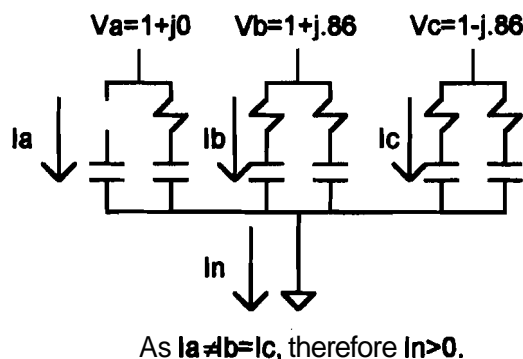


Figure 1a
Balanced System, Unbalanced Bank

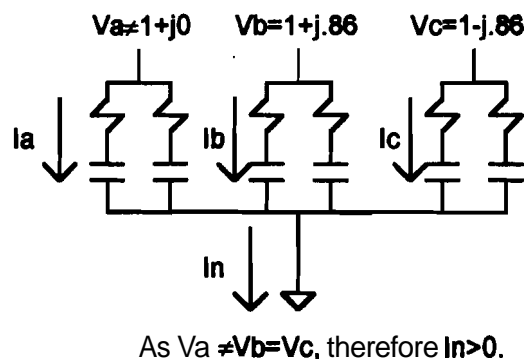


Figure 1b
unbalanced System, Balanced Bank

Figure 1 - Balanced and Unbalanced Conditions in a Grounded Wye Bank with Neutral CT

¹We are making the assumption that the capacitance of all of the capacitor units making up our bank are identical. In reality, there will be some steady state unbalance in a bank due to the fact that not all capacitor units of the same nameplate rating have identical capacitance values. This steady state unbalance is not usually a problem however and is easily compensated for by either adding the unbalance level to your relay settings, or using a relay that can compensate for it.

and they do not sum to zero at the neutral. The resulting current flowing from neutral to ground is then monitored by the CT shown.

Note however, that in Figure 1b the system phase to phase voltage is not balanced. This will also result in unequal current flow; not because of unequal phase impedance, but due to unequal voltages across a balanced bank. This unbalance scheme is referred to as non-compensating as it cannot compensate for external factors that cause unbalances within the bank. Now look at Figure 2.

Here we see what is referred to as a double wye, or split wye bank. The capacitor units are arranged into two equal half-sized capacitor banks connected in parallel. The key connection to note is that the two neutrals are connected through a CT. Now let us look at the two conditions again. First, a fuse operates on one phase in one wye (all bus voltages are equal). An unbalance now exists in that wye, and the three unequal phase currents cause a neutral current to flow from that wye through the CT.

If the bank is balanced but the phase voltages are not equal, we also get neutral currents in the bank, but also note that we get a neutral current out of each wye, of the same but opposite magnitudes. These currents cancel, and the CT sees nothing. In this way the relay scheme (actually the bank connection) has

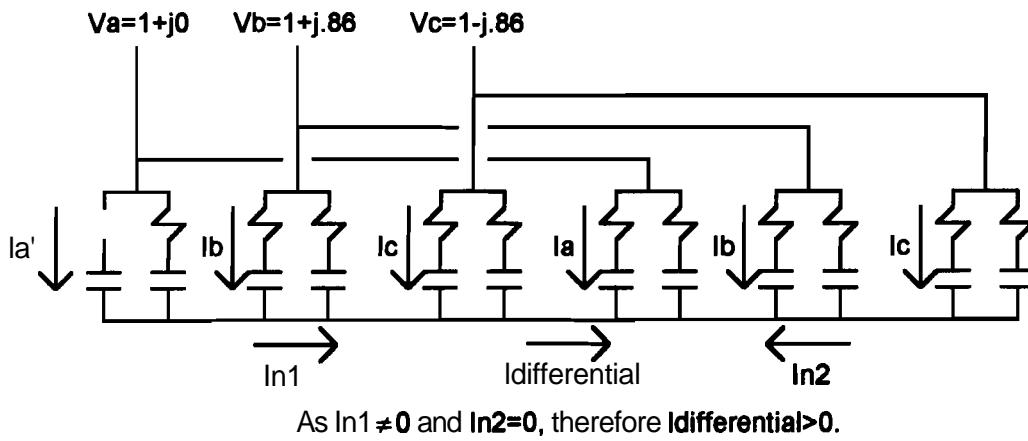


Figure 2a
Balanced System, Unbalanced Bank

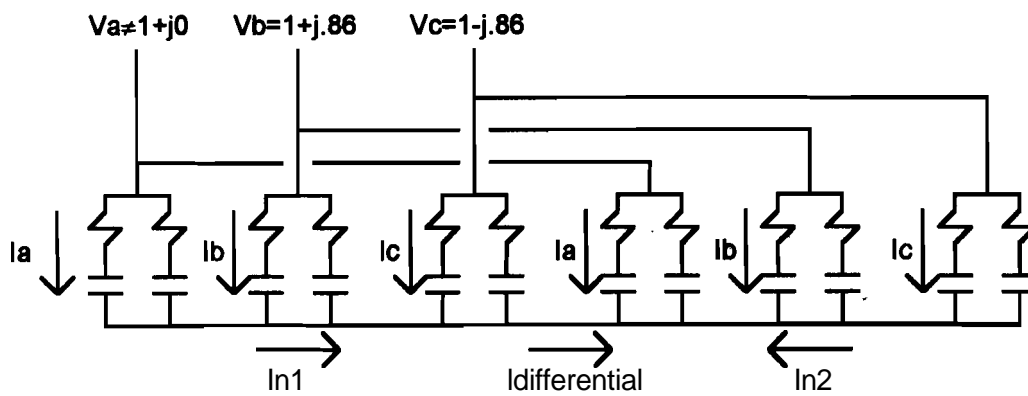


Figure 2b
Unbalanced System, Balanced Bank

Figure 2 – Naturally Compensating Double Wye Bank Arrangement

compensated for the system phase to phase voltage unbalance. This connection will actually compensate for any type of system unbalance including harmonics, faults, surges, transients, and so forth.

From this analysis one might conclude that the double wye connection is the best scheme, and in many cases this is correct. But for many applications the higher costs involved in implementing this scheme are not justifiable. The drawbacks of double wye banks are as follows:

- Smaller kVAr size capacitor unit must be used. Usually this scheme requires twice as many 1/2size capacitor units as a single wye bank. As smaller kVAr units are more expensive on a per kVAr basis, this increases the cost of the banks.
- Additional structure is necessary to hold the increased number of units. Also, for externally fused capacitors, twice as many fuse buses are required. Both of these also increase the cost of the bank.
- As double wye banks are generally larger than single wye banks, more substation space, and in some cases more foundation footings, may be required.
- For higher voltage banks² double wye bank configurations become unacceptable for the above reasons and other type of compensating relay schemes are then applied to conventional single wye banks.

When is a compensating scheme required?

Compensating schemes are only required if the expected phase to phase voltage unbalance in the system is such that it may cause a false ALARM or TRIP on the bank. The most common relay schemes are either a single wye bank grounded through a CT as described above, or a single wye bank grounded through a VT (essentially an ungrounded wye bank where unbalances cause a neutral to ground voltage shift, rather than a current flow). For these two bank connections, one can use some formulas and algebra to come up with an equation that indicates how much phase to phase voltage unbalance is required to generate a neutral current or voltage equal to that expected from the operation of a given number of fuses. In their most general form these equations are:

For grounded wye banks with neutral CT:

$$\%Unbalance_{system} = \frac{\%V_R - 100}{s - 1}$$

Where $\%V_R$ is the steady state overvoltage across the remaining connected capacitor units in the same series group in which the fuse(s) have operated that results in a TRIP signal³. If we make the assumption that the bank will TRIP at $\%V_R = 110\%$, then the formula simplifies to:

$$\%Unbalance_{system} = \frac{10}{s - 1}$$

For ungrounded wye banks with a neutral VT the equations are:

$$\%Unbalance_{system} = \frac{\%V_R}{3s - 2} \left(1 - \frac{100}{\%V_R} \right) \text{ and } \%Unbalance_{system} = \frac{10}{3s - 2}$$

² Typically 66/69 kV is a practical dividing line.

³ There are two assumptions used in deriving the formulas in this section. The first is that the bank is designed to be stable with one unit out of service. In other words, the loss of one fuse will not result in an overvoltage exceeded the accepted standard of 110% of the capacitor unit's voltage rating. The second assumption is that the voltage rating of the bank is equal to that of the system, i.e. the bank is not over-rated from a voltage standpoint.

Number of Series Groups in the Bank	Typical System Voltage Classes	Phase-to-Phase Unbalance Required to Simulate a 110% Unbalance	
		In Grounded Wye Banks	In Ungrounded Wye Banks
		Not Applicable ⁴	10%
1	4 – 34 kV	10%	2.50%
2	44 – 69 kV	5%	1.43%
3	66-115 kV	3.33%	100%
4	120 – 138 kV	2.50%	0.77%
5	145 – 161 kV	2.00%	0.62%
6	220 – 230 kV		

Table 1: Phase-to-Phase Voltage Unbalance Required to Simulate a Normal TRIP Operation

If one uses >110% steady state overvoltage as requiring a trip operation we can generate the information in Table 1. Note that for single series group banks, which are those most commonly applied up through 15 kV, a rather significant phase-to-phase voltage unbalance must exist before the false TRIP is generated. The level of system unbalance necessary to generate a false TRIP must be compared with the actual levels of phase-to-phase voltage unbalance that exists on your system. In most cases, for single series group banks, the more expensive double wye bank configuration is not necessary as the expected system unbalance is well below the high levels necessary to cause a false TRIP.

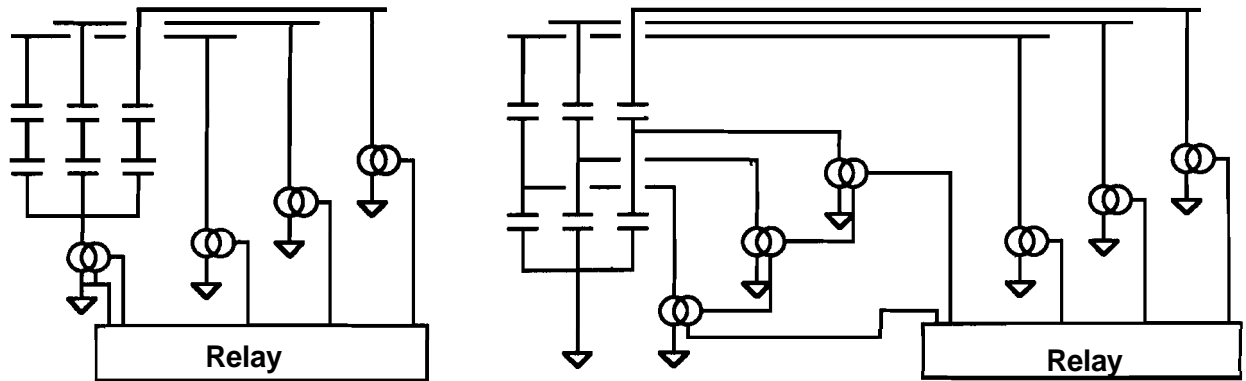
Note that grounded wye banks are inherently less susceptible to system unbalance than ungrounded wye banks.⁵ This means that the need to go to a compensating unbalance scheme is not as strong for grounded wye banks as the voltage class goes up. However, the increased sensitivity of both grounded and ungrounded single wye banks with increasing number of series groups does usually indicate that higher voltage banks will usually require a compensating type of relay scheme. It is interesting to note that though single wye banks do become more susceptible to system unbalance as the number of series groups increases, the higher voltage class systems these banks are used on generally limit system unbalance to lower levels, somewhat compensating for the increased sensitivity of the bank.

Typical Compensating Scheme for Single Wye Banks

At higher voltages where a compensating scheme is desired but a double wye bank is not, the most commonly applied relay scheme is shown in Figure 3. For ungrounded wye banks, the total unbalance is measured by a VT placed between the bank's neutral and ground. This device will then sense the neutral-to-ground voltage shift that occurs when an unbalance exists. For grounded wye banks, three VTs are used, one connected to the middle series group tie point of the capacitor bank in each phase. In this way the

⁴ As all capacitor units are connected from line to ground in single series group grounded wye banks there is no overvoltage produced on the remaining in service capacitors as a result of fuse operations.

⁵ See Kilovar Brief #2 for additional trade-offs between grounded and ungrounded substation banks.



Relay Connection for Ungrounded Wye Banks

Relay Connection for Grounded Wye Banks

Figure 3 – Compensating Unbalance Relay Scheme for Single Wye Banks

capacitor bank itself acts as a voltage divider circuit, allowing the use of lower voltage VTs. The outputs of these three VTs are then summed in an open delta connection to obtain an unbalance signal.

The relay also accepts inputs from three bus voltage monitoring VTs. These signals do not usually have to be sourced from dedicated VTs but may be supplied from existing VTs in the station. The bus voltage signals are summed to obtain an unbalance signal representative of the system unbalance only. The unbalance due to the system is then subtracted from the total unbalance signal. The remainder is the unbalance due only to the capacitor bank.

Summary

The following observations can be made about unbalance relay schemes:

1. Compensating schemes are sensitive only to internal capacitor bank unbalance. Non-compensating schemes are also sensitive to system unbalance.
2. Double wye banks are inherently immune to system unbalances but are more expensive to purchase and install than single wye banks.
3. For many applications, single wye banks and inexpensive non-compensating unbalance schemes are more than adequate to provide reliable performance.
4. For single series group banks, whether grounded or ungrounded, non-compensating schemes used on single wye banks are very effective as the level of system unbalance necessary to generate a false TRIP of the banks is usually much higher than that which normally occurs.
5. For higher voltage banks it is usually much more cost effective to install a single wye bank with a compensating unbalance relay scheme than to install a double wye bank.

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