Achieving Optimum Capacitor Bank Protection and Control

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Introduction

TVA applies shunt capacitor banks to their 161 kV system to regulate the local substation bus voltage over a range of light to heavy load and load switching conditions. The substation capacitor bank configuration may consist of up to 6 separately switched capacitor stacks. The entire substation bank is switched with a circuit breaker. The voltage level is monitored and used to switch in and out capacitor stacks as required for correct VAR compensation. The bus voltage is regulated to operate within a defined bandwidth around nominal voltage. There are two operating band widths that are used depending on load conditions, narrow band (NB) and wide band (WB). The number of capacitor bank stacks and bandwidths are determined by System Operations and Planning. Capacitor stack switching is either done manually or automatically. Automatic control must address several issues. Some of these are hunting – trying to find a stable voltage within an operating bandwidth, bandwidth operation transfer, auto to manual transfer and balanced switching operations of up to six capacitor bank capacitor switches over the life of the bank.

In addition to control a number of protection functions are also required. Each stack is protected with phase voltage unbalance 60 functions, which allows isolation of the faulted stack by operating the respective circuit switcher. Phase and ground overcurrent functions are provided that operate the circuit breaker for bus faults.

TVA has provided the aforementioned protection and control utilizing a programmable logic controller and six or more protection IEDs (Intelligent Electronic Device) as well as a number of switching control devices. This paper will discuss in detail the capacitor bank protection and control scheme and its implementation and testing on a new configurable substation IED, which incorporates the all the necessary protection and logic control functions.

Background

In the late 1990's, due to the large north-to-south power transfers across the system, TVA was faced with having to install 161kV capacitor banks at more than 50 sites. Up until that point TVA had created one-of-a-kind capacitor controls for each site that had limited functionality. Unfortunately, these one-of-a-kind control designs were plagued with operational problems so much so that the system dispatchers only operated most of them in the Manual mode.

With this avalanche of capacitor bank projects approaching, TVA engineers felt that a standard multifunctional protection and control scheme was needed that would operate correctly and the operators would not be afraid to enable automatic control. The trouble was that TVA's Transmission Planning Department would be requiring from two to six capacitor stacks per site and, and this could potentially lead to many design permutations.

Since a new standard was being developed, engineers had a "clean slate" to work with other than the finished product having to be compatible with existing substations. The compatibility requirement meant that such items like panel heights, alarm buses, equipment interfaces, terminal block locations, and number of terminal points available were compatible with all of TVA's vintage designs. Numerous requirements for the capacitor band protection and control package were discussed, but the following characteristics were selected as being needed in the TVA standard design:

1. Require as few hardware and software combinations as possible for all bank possibilities.
2. Provide breaker failure protection.
3. Provide phase 50/51 protection for the capacitor bus and capacitor bank.
4. Provide ground instantaneous overcurrent protection for the capacitor bus and bank.

5. Provide sensitive ground time overcurrent protection supervised by a 59N relay measuring bus 3V0 that would deliver backup protection for each stack's protection.
6. Provide primary voltage unbalance protection for each capacitor stack.
7. Provide local manual trip and close control of the breaker and capacitor switches that could be operated when transmission operators are on site.
8. Provide remote manual trip and close control of the breaker and capacitor switches.
9. Provide local automatic control consisting of WB and NB voltage control. This would also allow the local operator to select WB or NB control.
10. Provide remote automatic control consisting of WB and NB voltage control. This would also allow the dispatcher to select WB or NB control.
11. Provide operation equalization between the capacitor switches over the life of the bank.
12. Detect and control capacitor bank hunting when the control is in the automatic mode.
13. Provide engineered safety features consistent with TVA's standard operating philosophy and man-machine interface standards and expectations. An example of this would be to prevent automatic operation when in Manual or to prevent remote operation when in Local.

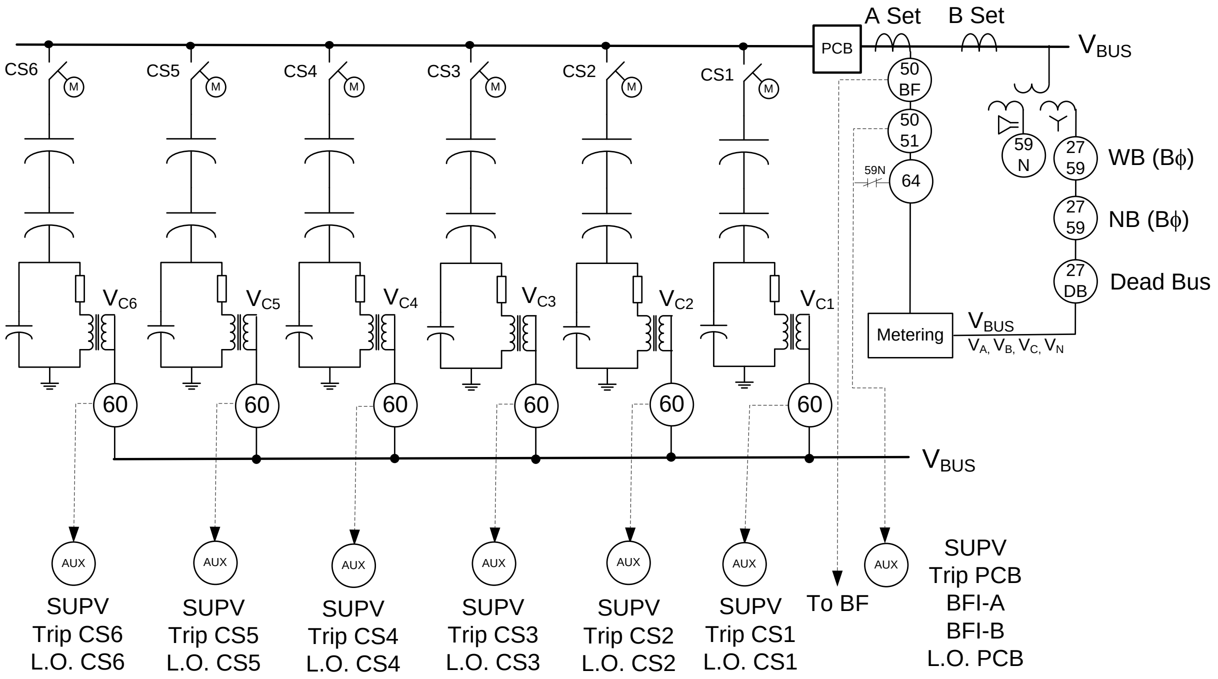
The above requirements led to the development of a single standard hardware and software arrangement that could protect and control up to six capacitor stacks. The standard scheme used two multifunction IEDs for capacitor bus and bank protection, one programmable logic controller (PLC) for control, up to six IEDs for individual capacitor stack protection (one for each stack), a single IED as a contact-making voltmeter to request raise and lower control operations through the PLC, and required various lockout relays, test switches, meters, and other control switches. Typically, TVA dedicated two full 19" racks of space for capacitor bank protection and control. Refer to Figure 1 for a single line diagram of a six bank installation. Today at green field sites, the standard design only uses four modern IEDs and the associated test switches. Switches, meters, and lockout relays have been incorporated into the IEDs, and TVA has reduced wiring by over 1100 terminations.

General Considerations

Protection

Two main areas of redundant protection are provided for in the IEDs. The first area is the protection of the individual capacitor stacks in Figure 1. This consists of using the capacitor stack neutral voltage measured across a low voltage capacitor (V_{C1} - V_{C6}) and comparing it on a phase-by-phase basis to the 161kV bus voltage (V_A, V_B, V_C) in a voltage balance function, device 60. This method provides a very sensitive element that is adjusted to detect individual capacitor element failures. A second device 60 element with a very short time delay will detect and trip for gross unbalances such as rack-to-rack faults in the associated stack.

The second area of protection is protection of the capacitor bus and capacitor bank, breaker failure protection for the PCB, and backup protection for stack failures. The capacitor bus and bank are protected by phase 50/51 elements to detect phase faults. Ground fault protection is provided by an instantaneous element, device 50N, and a sensitive element, device 51N-59N. The ground time overcurrent element, 51N, is unique in that it is supervised by a normally closed 59N element that measures the 3V0 on the supply bus. The 51N-59N combination is looking for minor unbalances in the capacitor bank. Such unbalances produce little or no 3V0. This combination allows the 51N element to be quite sensitive and it can be set to pickup just above the standing unbalance of the bank. The 59N should be set to assert for external faults and unbalances. Redundant breaker failure protection is also provided in the IEDs.



27 = B Phase undervoltage
27DB = 3-ph undervoltage dead bus
50BF = Breaker Failure current
50/51 = Phase overcurrent
59 = B Phase overvoltage

59N = 3V0 (measured or calculated)
60 = Voltage balance ($V = V_{BUS} - kV_{C1}$)
64 = 50N (3I0)
WB = Wide Band measured on B phase
NB = Narrow Band measured on B phase

Figure 1. Six Capacitor Bank Scheme

Indication, Measurement, and Control Switches

The standard design provides for current, voltage, and var indication displayed on the face of the IEDs. The IEDs also measure the bus voltage and assert logic bits when the capacitor stacks need to be switched ON or OFF. Voltage measuring elements are connected phase-to-ground and have an accuracy of better than 0.05%. Outputs of the voltage measuring elements assert or deassert to provide the WB raise and lower (27WB, 59WB) and NB raise and lower (27NB, 59NB) operating actions. During a forced outage such as a storm, TVA did not want the automatic control to mistake a “dead” bus as a “low” bus voltage condition and to stage all the capacitors ON. Upon reenergization, the bus voltage might become quite high, therefore, dead bus detection was provided. The 27DB undervoltage dead bus detection is provided to disable CS switching operations when the circuit breaker (PCB) is opened or the bus voltage is below 70% on all phases for a sustained period.

It is important to note that voltage element measuring accuracy is very important in high voltage applications such as these. When the raise and lower voltage settings are only a few kV apart, for example 163kV for raise and 165kV for lower, and the voltage transformer ratio is 1400:1, this leaves us measuring secondary voltages of 67.22V and 68.04V, respectively, and a difference of less than 1.0 volt. The relay must be able to accurately and reliably discriminate between two secondary voltages that may be less than a volt difference. The reader is urged to study manufacturer’s specifications carefully and avoid relays that have voltage element accuracies such as “+/- 1 volt and 2% of the setting” because this +/- 1 volt may be larger than the band in which the reader may want to regulate his voltage. The reader should also be wary of test data and claims that a relay is more accurate than the relay’s published specifications.

The current trend in the industry is to remove all switches from control panels. TVA is generally heading this direction as well. In the case of the capacitor bank control and protection, all control switches and all lockout relays, and indicating meters have been incorporated into the IEDs.

Control

The capacitor stacks are added or removed by capacitor switches CS1, CS2, CS3 . . ., and CS6 to regulate system voltage at the substation bus. Capacitor switches (CS) are controlled either manually or automatically. Logic is applied to balance their open and close operations throughout the life of the application. Following is a detailed description of the capacitor bank control scheme.

The scheme is easily scalable from 2-6 stacks by simply installing the needed stacks and associated protection equipment. If, for example, a capacitor bank required only four stacks, then only the equipment and wiring for stacks 1 through 4 would be installed. This method seems obvious, however, one fact that is not so obvious is that contained in the standard six bank logic are six logic gates similar to the one shown in Figure 2 whose output can be easily deasserted by setting of Disable to remove banks from the control scheme. In this example we would deassert banks 5 & 6 logic gates such that the control would ignore them since they are not installed. These gates are simply “Is stack installed?” gates. If the “Is stack installed?” gate is deasserted, the associated stack is not considered in the control scheme. These gates act as DIP switches to allow TVA to use a single IED program to easily control from 2-6 six capacitor stacks with no programming changes. Note that two banks were determined to be the minimum that we would install at a site.

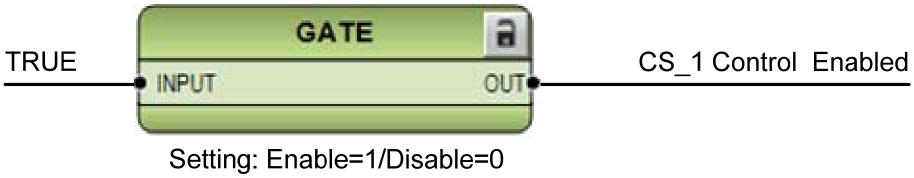


Figure 2. Logic Gates to Enable of Disable Capacitor Stack Control

Band Control

Control Voltage

The 161 kV system uses capacitor to regulate the bus voltage between (typically settings) 163 kV and 165 kV for small load changes and 161 kV and 168 kV for larger system load changes. Therefore, there are two voltage control bands, narrowband, 59NB/27NB and wideband, 59WB/27WB. These operating bands are illustrated in Figure 3.

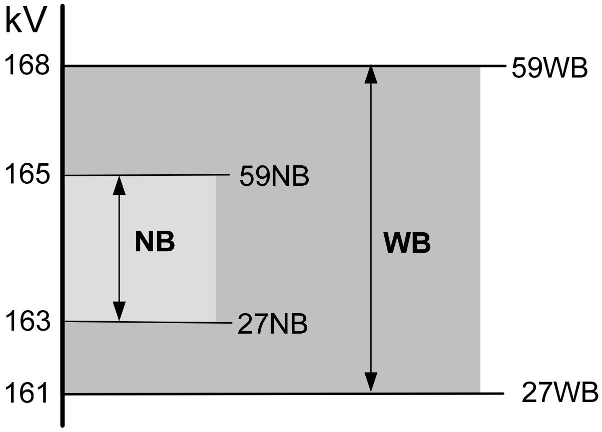


Figure 3. Typical NB and WB voltage level monitoring for a 161 kV bus

NB Operation

NB operation is set when expected load switching will be small and insertion or removal of capacitor stacks will regulate the voltage back into the NB region with stable operation until the next load change. If automatic operation is set to NB, no regulation (bank switching) is attempted while operating within the NB region. If there is a voltage excursion below the 27NB setting for a set time, NB Time (typically 60 to 120 seconds), then the next [in sequence] capacitor stack CS is closed and the NB timer is reset. If 27NB is still asserted for another period of NB time then the next CS is closed. This process is repeated until the voltage stabilizes within the NB region as expected or all the banks are closed.

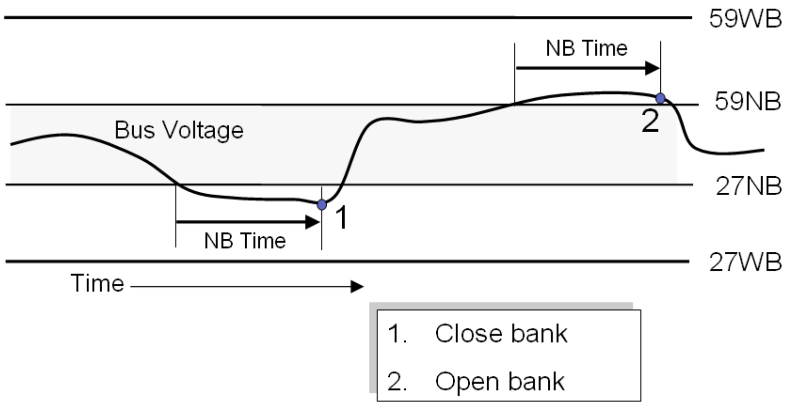


Figure 4. Normal NB operation

Similarly, if there is a voltage excursion above the 27NB setting for a set time, NB Time, then the next [in sequence] CS is opened and the NB timer is reset. If 27NB is still asserted for another NB Time then the next switch is opened. This process is repeated until the voltage stabilizes within the NB region or all the bank stacks are opened.

If, while set to NB operation, the voltage drops below the 27WB setting for a period of NB to WB Transfer Time, then the band operation is automatically switched to WB and WB timers. The NB to WB Transfer feature was provided to allow the control to quickly respond to major system voltage excursions by switching to WB and using the shorter WB time delays.

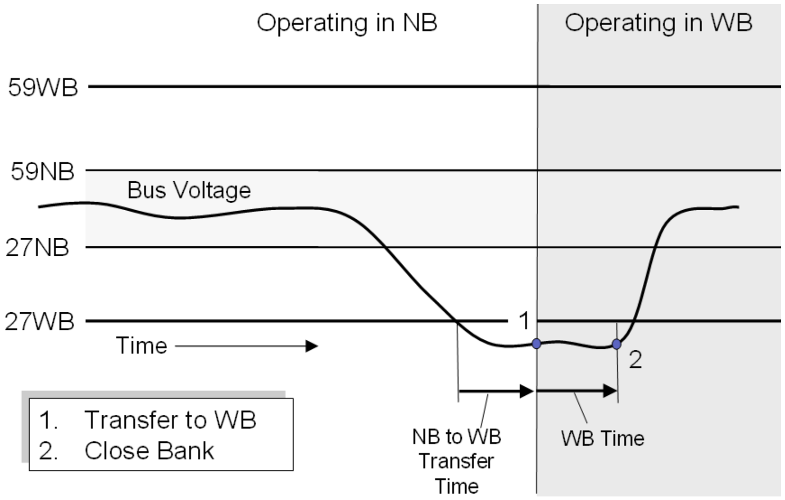


Figure 5. NB to WB Transfer

WB Operation

WB operation is set when load switching will be large and insertion or removal of capacitor stacks cannot regulate the voltage so that it stabilizes within the NB region. In this case voltage regulation is attempted in the WB region. If while operating in WB the voltage level exceeds the 59WB setting for a set time, WB Time (typically 15 to 30 seconds), the next [in sequence] CS is opened and the WB timer is reset. If 59WB is still asserted for another WB Time then the next CS is opened. This process is repeated until the voltage stabilizes within the WB region or all stacks are open.

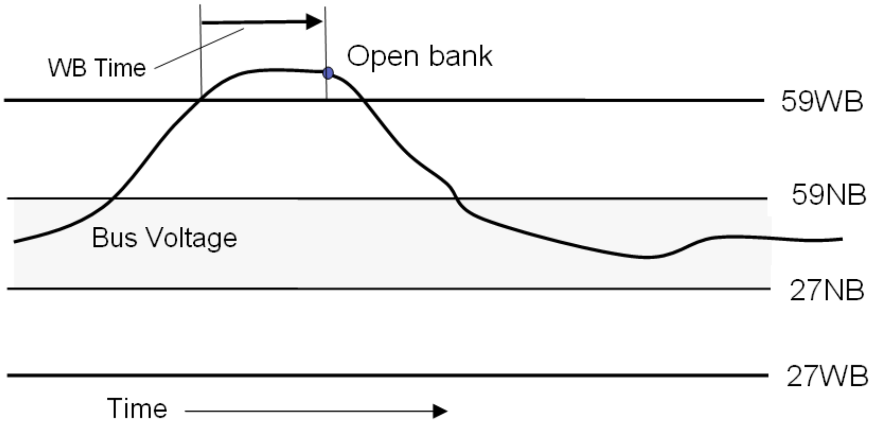


Figure 6. Normal WB operation

When the voltage level drops below 27WB setting for a set time, 27WB_Time (15 to 30 seconds), then the next [in sequence] CS is closed and the 27WB Timer is reset. If the 27WB is still asserted for another 27WB_Time then the next switch is closed. This process is repeated until the voltage stabilizes within the WB region or all the bank stacks are closed.

Hunting

Hunting is a condition where the voltage cannot stabilize within the band in which it is operating. The hunting logic is designed to detect open-close-open or close-open-close CS sequences within a time period that recognizes that voltage stability cannot be maintained with capacitor switching while operating in the set band, NB or WB. Depending on the operating band, different responses to hunting are taken.

NB Hunting

If, within a set time period of NB Hunting Transfer Time, there is a NB close-open-close operation, as illustrated in Figure 7, or open-close-open operation, then it is assumed voltage stability cannot be maintained within the NB region because the voltage compensation of the capacitor bank is too large for the given load conditions and the band operation is automatically switched to WB.

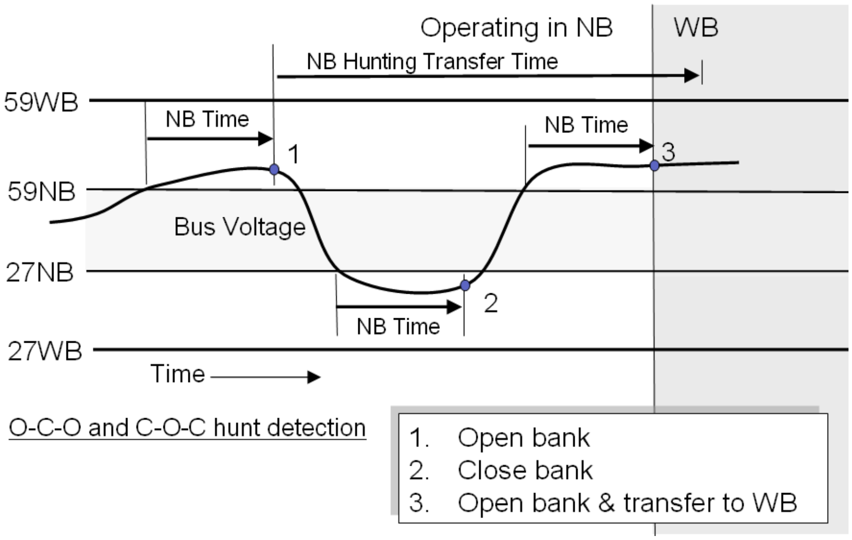


Figure 7. NB Hunting and Transfer to WB

WB Hunting

If, within a set time period of WB Hunting Transfer Time, there is a WB open-close-open or close-open-close operation then it is assumed voltage stability cannot be maintained within the WB region because the voltage compensation of a capacitor bank is too large for the given load conditions and the bank control is switched from Auto to Manual.

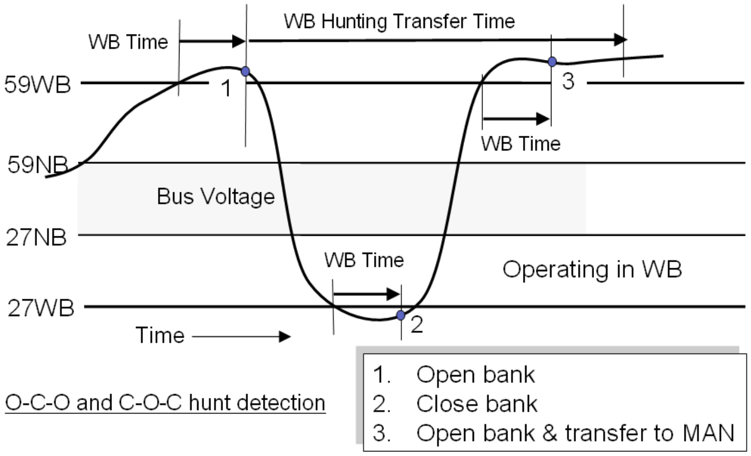


Figure 8. WB Hunting and Auto to Manual Control Transfer

Control Timer Settings

Typical timer settings used for NB and WB control and control transfer timers are provided in Table 1.

Table 1. Typical Control Timer Settings

Function	Seconds	Function	Seconds
59WB Time	15 - 30	59NB Time	60 - 120
27WB Time*[2]		27NB Time	
NB to WB Transfer Timer*[1]	0.5	NB Hunting Timer O-C-O / C-O-C	Minimum of 2.25 X NB Time
WB Hunting Timer O-C-O / C-O-C	Minimum of 2.25 X WB Time	Capacitor Switch # Just Opened Block Close Time	300

When selecting a time delay for the NB to WB Transfer Timer*[1], consideration must be given to how fast you want to begin correcting the low voltage condition. Normally, the voltage levels at TVA substations only gradually change throughout the day as the load increases or decreases. Sudden, sustained step changes in the voltage of a transmission bus are infrequent. TVA feels that when the bus voltage suddenly drops out of the narrow band range to a point below the wide band range that capacitor stacks should be staged on rather quickly. For this reason, the NB to WB Transfer Time is set to 0.5 seconds. Once the transfer to WB has occurred, the capacitor stacks will be staged on using the wide band time delays of 15-30 seconds.

TVA has used this capacitor bank control concept at a two capacitor stack installation associated with a nuclear plant. The nuclear plant is near a large city and the capacitor bank was installed for reactive support in the area and to avoid starting the plant's diesel generators on low bus voltage. As a result, the control at this site is adjusted to be very fast. In this application the NB to WB Transfer Timer*****[1] **and** the 27WB Time*****[2] are set at 0.5 seconds so the control can respond quickly when in either NB or WB. Including a 1.5 second circuit switcher operating time, two 90 MVAR stacks can be placed in service in less than 5 seconds. The 59NB Time, 27NB Time and the 59WB Times are set per Table 1 above.

Switch Operation Equalization Logic

Logic is provided to equalize the operation of all capacitor CSs. Open and close operations are handled independently. Easy implementation of the equalization logic is achieved using the stepping position switch as shown in Figure 9(a).

The stepping position switch allows the selection of only one of six positions, CL CS_1, CL CS_2 . . . and CL CS_6. If a position is selected then its output value is TRUE (logical 1) and if not selected the value is FALSE (logical 0). The signal CL EQ STEP (close equalize step) is a TRUE pulse input that will step the output from the current position to the next position as shown. Separate position switches are provided for independent OPEN and CLOSE operations of the CSs. Therefore, there is only one switch available to open and only one switch, which is generally a different one, available to close at any time.

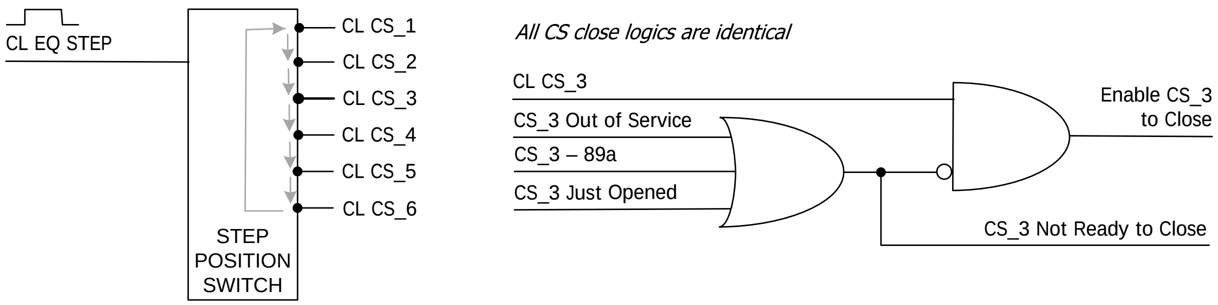
An Open Next CS or Close Next CS command is given from the voltage control logic shown in Figure 3 when the voltage increases above or drops below the band limits of its operation. It is at this time that the availability to open or close the next designated switch as identified by the stepping position switch output. There are six identical open and close CS availability logics, one for each CS. Figure 9(b) shows the CS availability to close logic for CS_3. There are four criteria required to enable CS_3 to close. The position switch output CL CS_3 must be selected (asserted) and CS_3 must be in service, open (89b=1 or

89a = 0), and CS_3 cannot have just opened. The signal CS_3 Just Opened is asserted when CS-3 opens to block closing of CS_3 for a set time to allow dc voltage discharge of the capacitor stack. If the criteria are satisfied then the signal Enable CS_3 to Close is asserted. Otherwise the signal CS_3 Not Ready to Close is asserted.

Figure 9(c) shows the Enable CS_3 to Close and Closed Confirmation Logic. A close command is given to CS_3 and when it is closed the change of state of the auxiliary switch CS_3 89a from OFF to ON occurs and asserts a CL EQ STEP pulse to move the position switch to CL CS_4.

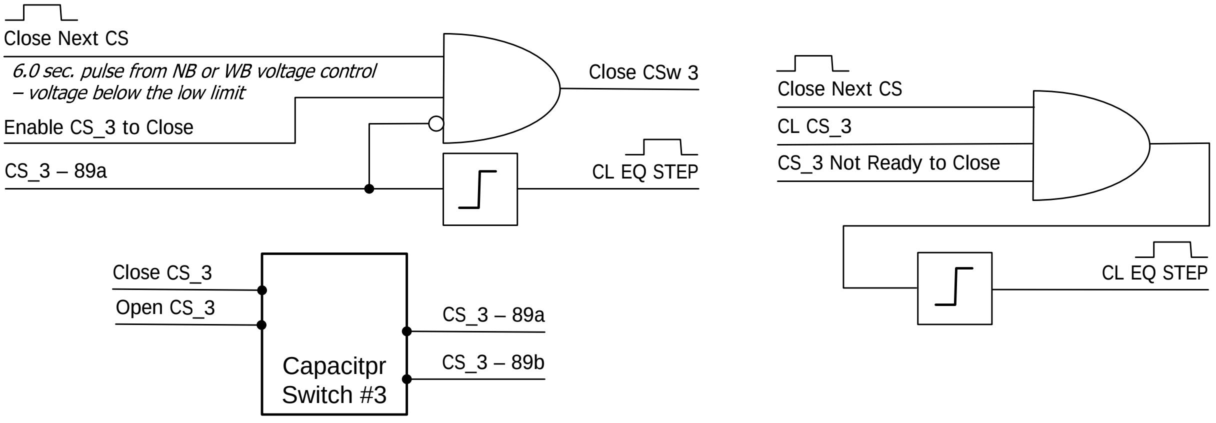
Figure 9(d) shows the CS_3 Not Available to Close Logic. It basically asserts a CL EQ STEP pulse to move the position switch to CL CS_4. This process is repeated until a CS is found that can be closed or that there are no CSs available to close (all are already closed).

Equalization logic can operate in both manual and automatic modes. When in the manual mode, manual equalization control automatically selects the next CS to be opened or closed from a virtual switch on the HMI. When in the automatic mode, the equalization control automatically selects the next CS to open or close based on system voltage conditions previously discussed.



(a) Stepping Position Switch

(b) CS Availability to Close Logic



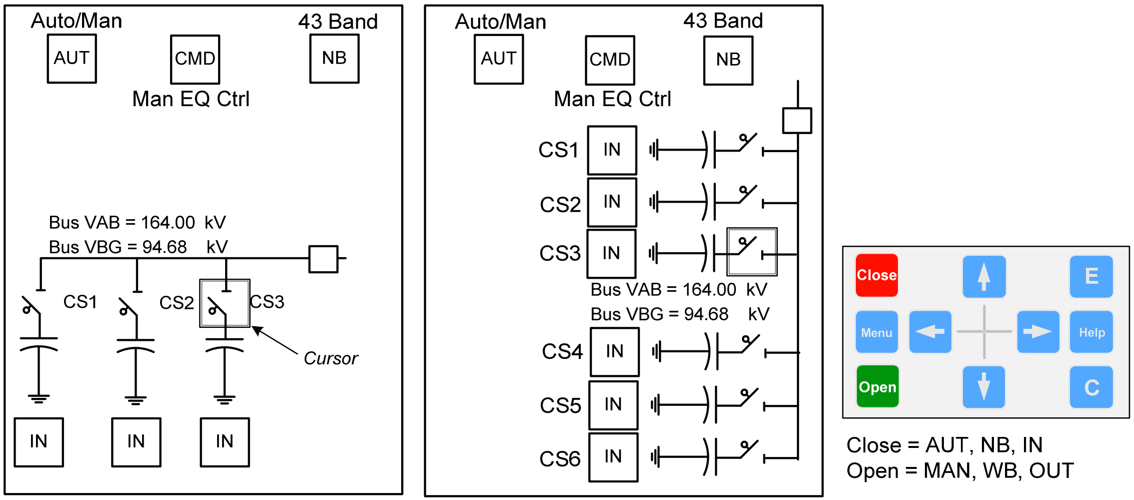
(c) Enable CS_3 to Close and Close Confirmation

(d) CS_3 Not Availability to Close

Figure 9. Capacitor Switch Operation Equalizer Logic

Local Control (HMI Operation)

When the Local/Remote switch at the IED is in the Local position, local control can be performed. Figure 10 shows two arrangements of the HMI screen graphic controller, which along with the front panel ↑↓ navigation keys and Open & Close buttons provide the appropriate local control for automatic or manual operation. The screens are configurable and may be modified to fit the number of capacitor stacks in the bank. The cursor, which is presently on CS_3 for both examples, is moved with the ↑↓ buttons from one controllable device to another. Then the respective virtual switch position: Close or Open, ON or OFF, AUT or MAN, NB or WB control command is made with the Close or Open button on the IED.



(a) Three Stack Control (b) Six Stack Control (c) Navigation keys

Figure 10. Front Panel HMI Graphic Control

There are one circuit breaker and two to six capacitor switches, CS1/#1, CS2/#2, CS3/#3, etc. that can be manually controlled. There are also a number of two-position "virtual" switches – 5 for control configuration and 2 to 6 for placing a CS in or out of service. Table 2 shows the function of the virtual switches.

Table 2. HMI Virtual Switch Operation

Virtual Switch	Pos	Operation
Auto/Man	MAN	Permits manual operation of the circuit breaker and capacitor bank circuit switches from the HMI graphic controller.
	AUT	Puts the control of capacitor bank capacitor switches in the automatic mode and blocks manual operation. Enables hunt detection and NB to WB transfer.
Man EQ Ctrl	CMD	Provides switch operation equalization while the Auto/Man switch is in MAN. The switch is momentary and provides an open or close pulse to the next switch scheduled to be operated. Operation is effected by the Open or Close button.
43 Band	WB	Band control is currently WB.
	NB	Band control is currently NB.
CS# Service	OUT	CS# is out of service and cannot be operated.
	IN	CS# is in service.
CS# Control Switch	Open	Opens capacitor switch while in manual control.
	Close	Closes capacitor switch while in manual control.

Remote Control

When the Local/Remote switch at the IED is in the Remote position, TVA operators at the system control center have the same control and status indications as the local operator would have being onsite at the substation. This information access is possible with contact RTU I/O, DNP 3.0, or IEC 61850.

Testing

To facilitate testing a modern test set that provides programmed state sequence testing and 7 breaker simulators were used.

Protection

Normal testing procedures as applied to other IEDs were used for all protection functions.

Manual Control

With Auto/Man set to MAN control operations were performed by operating each CS open and close several times and in random order to assure correct wiring interconnections and graphical HMI control programming. When satisfied of correct connections and programming the operation counters for each CS were reset from the front panel reset button. The CSs were then operated with the Man EQ Ctrl virtual switch 60 or so times of random open and close commands (e.g. OPEN, OPEN, OPEN, CLOSE, OPEN, CLOSE,CLOSE, OPEN, CLOSE, CLOSE, CLOSE, etc.) to verify balanced operation.

Automatic Control

Band Control Voltage Levels

The pickup and dropout accuracy of the 59WB, 59NB, 27NB and 27WB was tested to assure sufficient measurement resolution (voltage level steps) between the NB and WB levels. For the typical 161 kV application settings of Table 3, the secondary voltage difference between the NB upper and lower levels is 0.82 volt. Therefore a test resolution step of 0.1 V secondary was used.

Table 3. Control Voltage Band Levels

Band Control	Primary Volts ΦΦ	Primary Volts ΦG	VT Ratio	Secondary Volts ΦG
59WB	168,000	96,995	1400	69.28
59NB	165,000	95,262	1400	68.04
Nominal	164,000	94,685	1400	67.63
27NB	163,000	94,108	1400	67.22
27WB	161,000	92,953	1400	66.40

Procedure for Testing NB and WB Voltage Levels

1. Set Auto/Manual control to MAN.
2. Using Table 3 as a reference set the primary NB and WB voltage 27 and 59 limits.
3. Apply a balanced three-phase secondary voltage level of nominal voltage, 67.6 V secondary and check primary value on front panel LCD.
4. Increment the voltage level up on all three phases with 0.1 V steps on the test set until 59NB operation is indicated. Record and compare to the 59NB value of Table 3.
5. Increase further until 59WB operation is indicated. Record and compare to the 59WB value of Table 2.
6. Increment the voltage level down and observe dropout of 59WB and 59NB.
7. Reset the secondary voltage level to nominal voltage, 67.6 V.

8. Increment the voltage level down on all three phases with a 0.1 V step until 27NB operation is indicated. Record and compare to the 27NB value of Table 2.
9. Decrease the voltage further until 27WB operation is indicated. Record and compare to the 27WB value of Table 2.
10. Increment the voltage level up and observe dropout of 27WB and 27NB.

Automatic Control

Sequence testing was used to verifying the various auto switch control functions. All CSs were closed and the CS operations counter for all switches were reset. This allowed counting CS operations during the test period. For each test, assurances were made that the first operation state does not affect a switch operation that cannot be made. For example, a 27NB level voltage will attempt to close a CS and if all CSs are already all closed this cannot be done. Therefore, each test was planned carefully. When it was necessary to manually open or close a CS the Man EQ Ctrl switch was used.

Following are some test sequence test examples.

NB Operation

Set Auto/Manual operation to AUT and 43 Band to NB. Using the following sequence NB operation was tested and operations observed. There was no NB to WB transferring – 43B Band was still in NB. There were two CS open and one CS close operations.

Table 4 NB Operation

	State 1	State 2	State 3	State 4
Sec. Voltage	Nominal	59NB level + 0.5	Nominal	27NB level – 0.5
Duration – Sec.	5	59NB Time + 0.5	1.1 X NB Hunt Time	27NB Time + 0.5
Operation		CS opened		CS Closed
	State 5	**State 6**	**State 7**	
Sec. Voltage	Nominal	59NB level + 0.5	Nominal	
Duration - Sec.	1.1 X NB Hunt Time	59NB Time + 0.5	5	
Operation		CS opened		

NB to WB Transfer

The observed virtual switch positions were Auto/Manual operation on AUT and 43 Band on NB. Using the following sequence the NB to WB transfer was tested. NB to WB transfer could be observed on the 43 Band virtual switch icon, the setting label will change from NB to WB. There was a NB to WB transfer followed by a close CS operation. The 43 Band switch was left in WB.

Table 5 NB to WB Transfer

	State 1	State 2	State 3	State 4
Sec. Voltage	Nominal	27WB level - 0.5	27WB level - 0.5	Nominal
Duration – Sec.	5	NB-WB Transfer Time + 0.2	27WB Time + 0.5	5
Operation		NB to WB transfer	CS closed	

WB Operation

The observed virtual switch positions were Auto/Manual operation on AUT and 43 Band on WB. Those were correct after the above sequence tests. Using the sequence test of Table 4 except substituting WB voltage and timer values for NB values, WB operation was tested. There were two CS open and one CS close circuit operations.

NB Hunting and Transfer to WB

The observed virtual switch positions were Auto/Manual operation on AUT and 43 Band on WB. The 43 Band switch was then reset to NB. Using the sequence test of Table 6 NB hunting and transfer to WB operation were tested. There was a NB to WB transfer – 43B Band was changed from NB to WB. There were two CS close and one CS open operations. The close-open-close operation within the NB Hunt Time established the hunting condition.

WB Hunting and Transfer to Manual

The observed virtual switch positions were Auto/Manual operation on AUT and 43 Band on WB. These were the correct switch positions considering the previous tests. Using the following sequence WB hunting and transfer to manual operation was tested. There were two CS open and one CS close operations. The open-close-close operation within the WB Hunt Time established the hunting condition and the AUT to MAN transfer. There was an Auto/Man transfer – Auto/Man is now in MAN.

Table 6, NB Hunting and Transfer to WB

	State 1	**State 2**	**State 3**	**State 4**
Sec. Voltage	Nominal	27NB level - 0.5	Nominal	59NB level + 0.5
Duration – Sec.	5	27NB Time + 0.5	0.5	59NB Time + 0.5
Operation		CS closed		CS opened
	State 5	**State 6**	**State 7**	
Sec. Voltage	Nominal	27NB level - 0.5	Nominal	
Duration - Sec.	0.5	27NB Time + 0.5	5	
Operation		CS closed		

Table 7 WB Hunting and Transfer to Manual

	State 1	**State 2**	**State 3**	**State 4**
Sec. Voltage	Nominal	59WB level + 0.5	Nominal	27WB level – 0.5
Duration – Sec.	5	59WB Time + 0.5	0.5	27WB Time + 0.5
Operation		CS opened		CS Closed
	State 5	**State 6**	**State 7**	
Sec. Voltage	Nominal	59WB level + 0.5	Nominal	
Duration - Sec.	0.5	59WB Time + 0.5	5	
Operation		CS opened		

Summary

TVA has been able to meet its design objectives of combining protection and control requirements into a minimum number of boxes. One IED can provide complete bank protection and control for capacitor banks with up to six switchable capacitor stacks. The IED can also provide phase-voltage unbalance for up to three switchable stacks. A second IED is required to provide phase-voltage unbalance protection for capacitor banks with 4 to 6 switchable stacks. In addition, redundant bank protection is also provided in the second IED. The basic objectives provided and reviewed are:

- A single scalable design that allows protection and control of a capacitor bank with up to six switchable stacks.
- Comprehensive capacitor protection including breaker failure, phase and ground protection for the bus and capacitor bank faults and sensitive phase voltage unbalance protection for each capacitor stack.
- Engineered safety features of exclusive Local or Remote and Manual or Automatic control.
- Automatic voltage control consisting of NB and WB voltage regulation with hunt (unable to stabilize voltage within the band) detection and band transfers.
- Manual trip and close control the breaker and capacitor switches.
- Logic to equalize CS operations over the life of the capacitor bank in both manual and automatic modes.
- Reduces the number of IEDs, elimination of external switches, indication meters and other external components.
- Reduces the switchboard space requirements and terminations.

In addition, focused attention was given to explaining voltage control, CS operation equalization logic and their testing for the reader to develop a better concept understanding.

Biographies

Robert Frye is an Electrical Engineer Specialist in the System Protection & Analysis department at the Tennessee Valley Authority in Chattanooga, TN. He is responsible for calculations and setting protective relays in the TVA transmission system and at hydro, fossil, and nuclear plants. Prior to his position in System Protection & Analysis, he was a Principle Engineer in the Electric System Projects, Protection and Control Department and he was a System Engineer at Watts Bar Nuclear Plant. Robert is a registered professional engineer in Tennessee, and he earned his B.S.E. degree from the University of Tennessee at Chattanooga. Robert is a member of the IEEE Power System Relaying Committee. Robert is can be contacted at rmfrye@tva.gov

Jay Hicks is a Regional Technical Manager serving the Southeast Region for ABB, located in Chattanooga, Tennessee. Primary responsibility is to support ABB's high voltage line of protective relays and controllers. Prior to his work at ABB, Jay was a Senior Protection and Control Engineer at Tennessee Valley Authority. He was responsible for the Protection and Control design package, consisting of calculations, drawings, inter- departmental interface documents, and construction assisting documents for substations and switchyards. Jay graduated from Tennessee Technological University with BSEE degree and is a member of IEEE. Jay can be reached at jay.b.hicks@us.abb.com

Elmo Price received his BSEE degree in 1970 from Lamar State College of Technology (Lamar University) in Beaumont, Texas and his MSEE degree in Power Systems Engineering in 1978 from the University of Pittsburgh.

He began his career with Westinghouse in 1970 and worked in many engineering positions that included assignments at the Small Power Transformer Division in South Boston, VA, the Gas Turbine Systems Division in Philadelphia, and T&D Systems Engineering in Pittsburgh. He also worked as a District Engineer located in New Orleans providing engineering support for Westinghouse power system products in the South-central U.S.

With the consolidation of Westinghouse into ABB in 1988 Elmo assumed regional responsibility for product application for the Protective Relay Division. From 1992 to 2002 he has worked at both the Coral Springs, Florida and Allentown, Pennsylvania Divisions in various technical management positions responsible for product management, application support and relay schools. From 2002 to 2008 Elmo was the Regional Technical Manager providing product sales and application support in the southeastern U.S.

Elmo is currently Senior Consultant for ABB and is located in Dawsonville, Georgia. Elmo is a registered professional engineer and a Life Senior member of the IEEE. He is a member of the IEEE Power System Relay Committee and the Line Protection Subcommittee, serving as a contributing member to many working groups. He has two patents and has authored and presented numerous industry papers.