Hands-On Relay School

Testing Breaker Failure Schemes

Valence Electrical Training Services

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1. Introduction

The power system is a delicate balance between load and generation. We usually think that brownouts and blackouts are only caused by faults on the system, but they can also occur when the load is greater than the available generation; or when there is more generation available than load. Protective relays detect faults and isolate them from the rest of system before they destabilize the entire grid and cause system-wide outages. History has shown that every extra moment a fault is energized can destabilize a larger part of the power grid. All transmission system protection is designed to minimize the fault time to protect the entire grid. Every cycle counts!

Any important node on the power system will have:

- An isolating device (circuit breaker/circuit switcher) to energize and isolate a section of the power system.
- Instrument transformers (CTs/PTs) to reduce the primary voltage and/or currents to smaller, secondary values to minimize the size of protection equipment.
- A protective relay that measures the CT/PT secondaries and equipment status to detect problems on the power system that should be isolated.
- A separate power supply for the protection and isolation equipment that operates under all power system conditions.

Electrical Engineers are constantly asking themselves “What if?” questions, trying to make the power system more reliable and stable. A cost/benefit analysis is applied to each “What if?” question. More questions will be asked if the equipment is vital to power system stability, or expensive. Transmission circuit breakers have a lot of questions because they are vital to power system stability. Some of those questions and answers include:

- What if the PT fuse(s) operate? Add Loss-of-Potential logic that blocks any element that uses voltage in its calculations.
- What if the zone of protection is large enough to trip when an overload occurs? Add a Load Encroachment, or Fault Current-detector, blocking element that helps the relay tell the difference between faults and overloads.
- What if the fault is still on the circuit when you close the breaker? Add Switch-Onto-Fault logic to trip the circuit breaker immediately instead of waiting for the normal time delay.
- What if the circuit breaker trip circuit fails? Add a redundant trip circuit with a unique power supply, inputs, and trip coil.
- What if the protective relay fails? Buy a different model relay with the same functions and install it as secondary protection that detects faults and trips the circuit breaker.

- What if the trip coil circuit opens? Add Trip Coil Detection circuitry to provide an alarm if a problem with the trip coil circuit is detected.
- What if both primary and secondary protective relays fail? Add backup protection on adjacent nodes with extended time delays that gives the circuit breaker plenty of time to trip after its local relays detect a fault.

There are plenty more "What if?" questions left, but the circuit breaker is still a weak link after all the other contingencies are accounted for. Breaker fail protection answers the question: "What if the circuit breaker fails to open during a fault?"

The power system depends on transmission circuit breakers opening when the protection and control system sends an "open" command. However, any of these circuit breaker problems could prevent them from opening:

- The trip coil can't operate when there is low, or zero, DC trip voltage at the circuit breaker.
- The trip coil(s) could be mechanically or electrically damaged and unable to operate.
- The tripping latches could be out of alignment and unable to release.
- The trip mechanism could be out-of-alignment or damaged.
- The primary dielectric might not be able to quench the arc created when the contacts open because it is contaminated, low, or missing.
- The primary contacts could be fused closed.
- The fault current could be higher than the circuit breaker's opening ratings.

2. What Should Happen When a Fault is Detected

Before we dig into breaker failure schemes, let's look at what is supposed to happen in a perfect world when a fault occurs between breakers 3 and 4, as shown in Figure 1.

Breakers 3 and 4 should both operate with no intentional time delay via their Line Distance (21), Zone 1 protection, or Line Differential (87L) protection, as shown in Figure 2. The ideal worst-case scenario happens when one relay on the line detects a Zone 1 fault and operates with no intentional time delay, then the other relay trips 15-25 cycles later after detecting a Zone 2 fault. Either way, the fault is isolated from the system with minimum disruption because L2 is the only load that is offline after the relays operate.

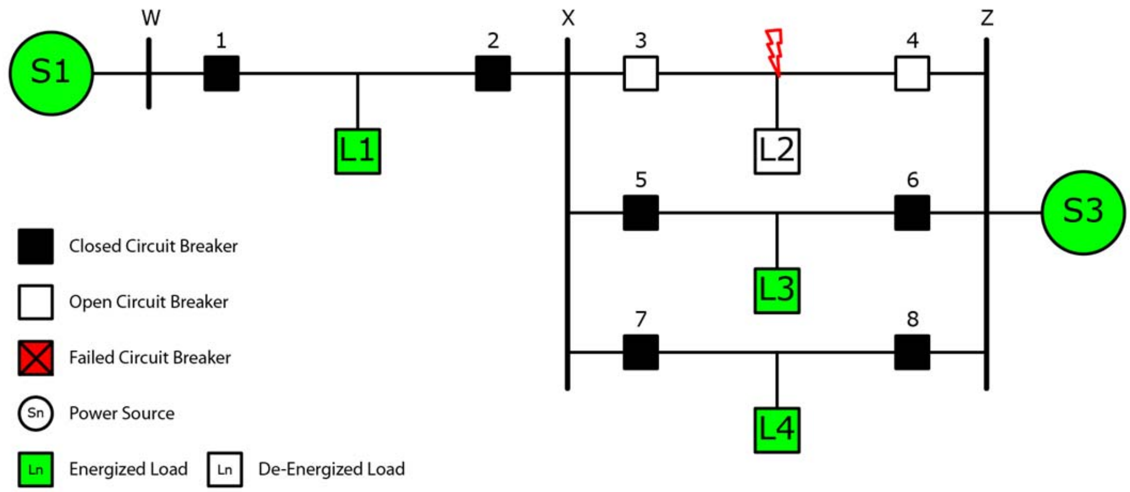


Figure 1: Standard Single-Line Drawing

Figure 2 shows a time graph of the entire tripping process with both relays operating with no intentional time delay. The Total Fault Clearing Time in an ideal world equals the Local Protective Relay Time and the Breaker Interrupt Time. The Total Fault Clearing Time must be faster than the Critical Clearing Times, otherwise the rest of the grid may destabilize. You should notice that an element with "no intentional time delay" has a number of hidden time delays that occur in the real world. "Instantaneous" elements aren't really instantaneous.

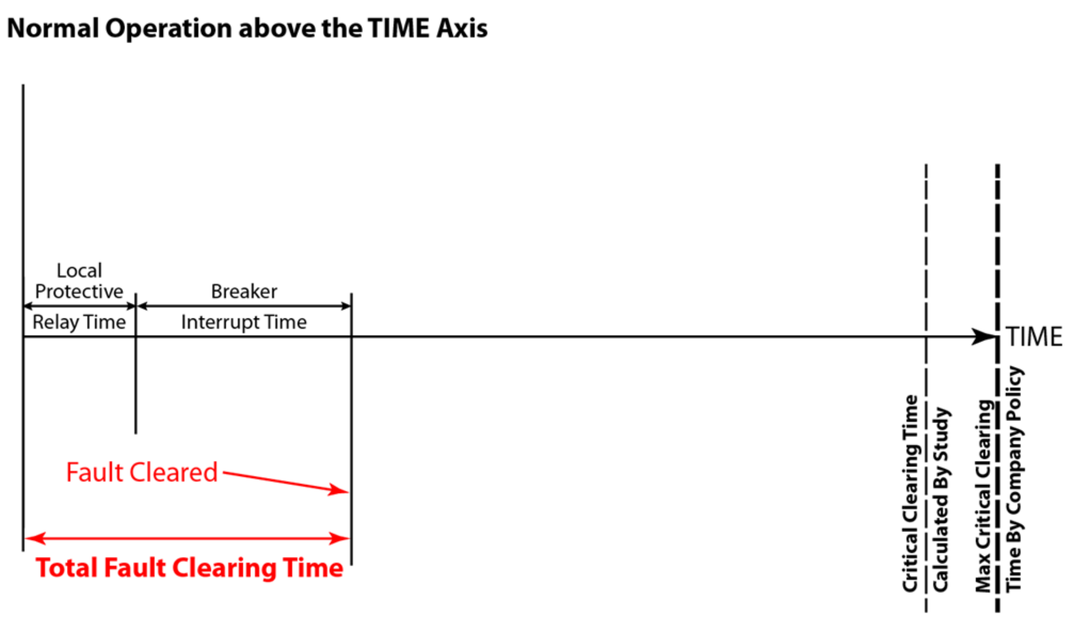


Figure 2: Standard Tripping Times

All of the information in Figure 2 can be summarized with the following descriptions:

- "TIME" is the X-axis, which organizes all time delays involved that isolate a fault from the power system.
- "Local Protective Relay Time" is the amount of time required by the relay to:
  - analyze the input waveforms,
  - detect the fault with calculations or pattern recognition,
  - ensure the fault is on the system longer than the expected time delay,
  - send a trip signal to its internal output contacts, and
  - close its internal output contacts.
- "Breaker Interrupt Time" is the amount of time that the breaker takes to open and isolate the fault when a trip signal is received under normal conditions.
- "Fault Cleared" indicates the moment that the fault has been successfully isolated from the rest of the power system.
- "Total Fault Clearing Time" is the sum total of all time delays required to isolate the fault from the rest of the power system.
- "Critical Clearing Time Calculated by Study" is the maximum amount of time that the fault can stay on the system at that specific location before the system becomes destabilized. The fault must be cleared within this time delay to prevent a cascading system-wide failure.
- "Critical Clearing Time Calculated by Company Policy" is a safety margin that the utility applies to all transmission lines to prevent system-wide cascading failures. The fault should be cleared within this time delay.

Figure 3 shows what happens when something goes wrong with the local protection and the remote Zone 2 backup protection in the relays connected to Breakers 1, 4, 6, and 8 operates instead. All four loads are now de-energized instead of just the load closest to the fault. The entire local power grid could also be in jeopardy because the delicate balance between generation and load could be tilted too far toward generation and cause problems everywhere.

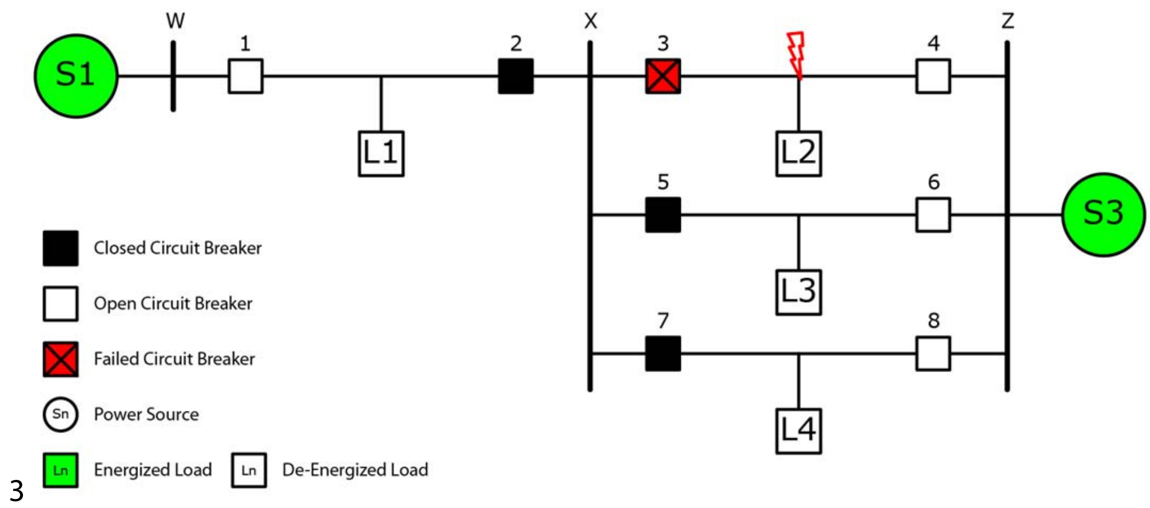


Figure 3: Single-Line Drawing after a Zone 2 Trip

The time graph in Figure 4 shows what happens when the backup protection operates. Notice that the Total Fault Clearing Time is significantly longer than it was when the local relays tripped. The time delay could be longer than the Critical Clearing Times as well, which would destabilize the entire grid.

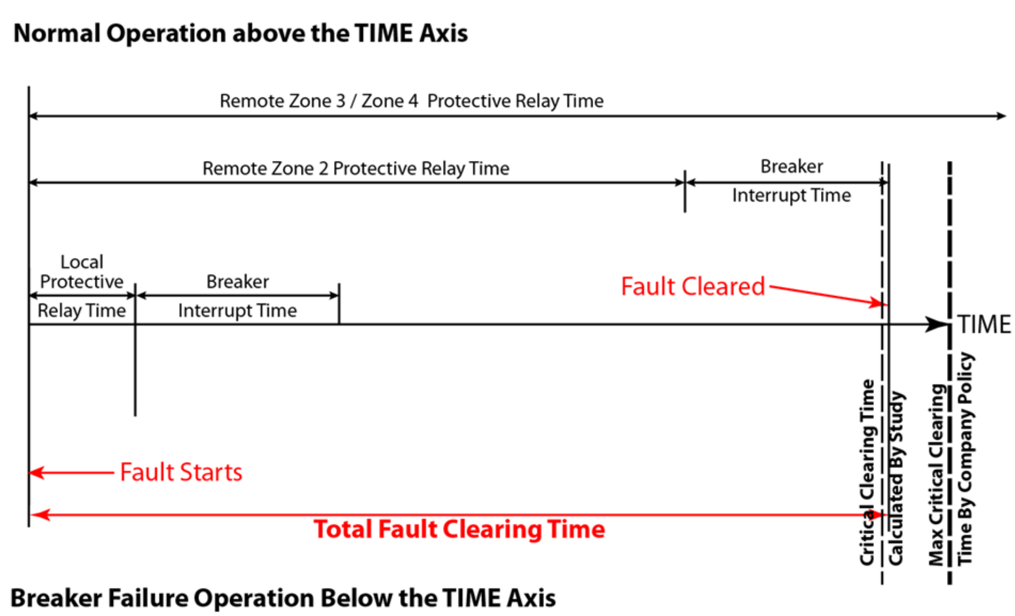


Figure 4: Backup Protection Tripping Times

The situation changes with a Breaker Failure scheme, as shown in Figure 5. The Breaker Failure scheme received a trip signal when the relay tripped and waited for the circuit breaker to open. The circuit breaker did not open before the Breaker Failure Timer expired, so the Breaker Failure Scheme opened all of the circuit breakers directly connected to the failed circuit breaker to isolate the fault from the system. The three non-faulted loads were still energized after the fault was cleared, as they were when the local protection operated. The Breaker Failure Scheme prevented the catastrophe that occurred when the remote backup protection operated.

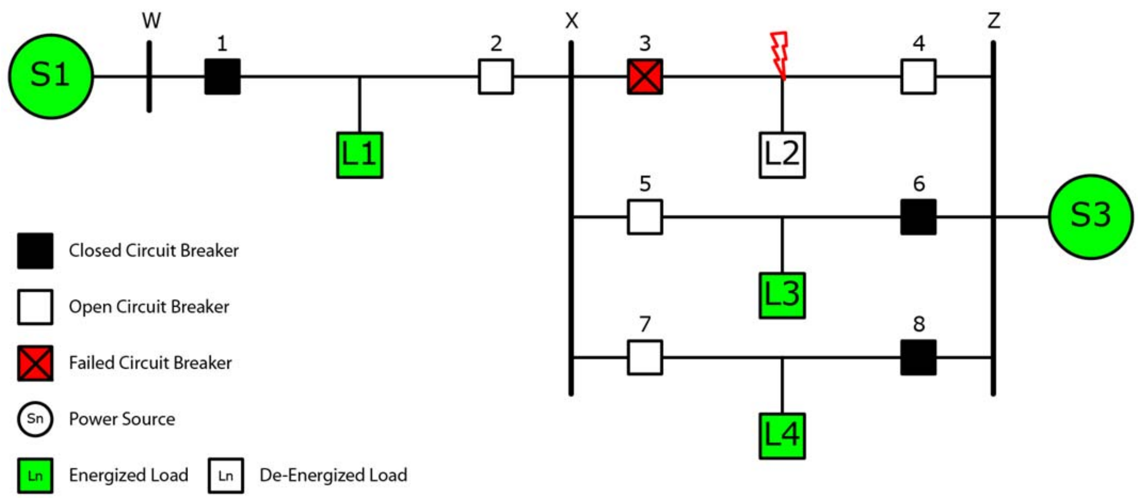


Figure 5: Single-Line Drawing after a Breaker Failure Trip

The time graph in Figure 6 shows the time delays associated with a Breaker Failure scheme.

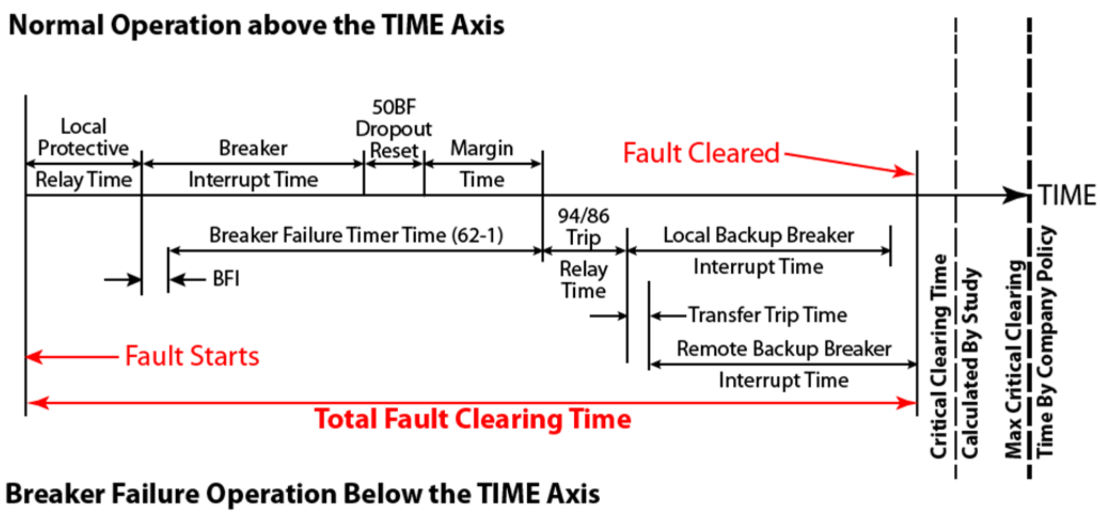


Figure 6: Breaker Failure Tripping Times

The new time delays in Figure 6 can be summarized with the following information:

- "BF Dropout Reset" allows time for the Breaker Failure element (50BF) to disarm itself after the circuit breaker opens to prevent mis-operations.
- "Margin Time" is an extra fudge factor to account for any problems that could slow the breaker opening time.
- "BFI" is the time it takes the Breaker Failure Scheme to sense the trip signal sent to the circuit breaker.
- "Breaker Failure Timer Time (62-1)" is the setting that determines how long the Breaker Failure Scheme waits before sensing that the local breaker has failed before it starts opening all of the circuit breakers required to isolate the failed circuit breaker.
- "94/86 Trip Relay Time" is the time it takes for any external relays to recognize the Breaker Failure Trip, and send a trip signal to all the associated circuit breakers that should trip to isolate the failed circuit breaker.
- "Local/Remote Breaker Interrupt Time" is the local breaker opening time to isolate the fault when a trip signal is received under normal conditions.
- "Transfer Trip Time" is the time delay that occurs when a trip signal is sent through communication equipment.

All faults should be cleared before the Critical Clearing Time. Breaker Failure Schemes allow the design engineer to ensure this happens locally without relying on backup protection.

3. Basic Breaker Failure Protection Schemes

Basic Breaker Failure Schemes are pretty straightforward, as shown in Figure 6. The Breaker Failure Timer will start if the circuit breaker is closed AND the circuit breaker receives a trip signal. If the circuit breaker opens before the Breaker Failure Timer times out, the Breaker Failure protection will disarm itself. If the Breaker Failure Timer times out, a Breaker Failure Trip command will be sent to all the other circuit breakers connected to the failed circuit breaker.

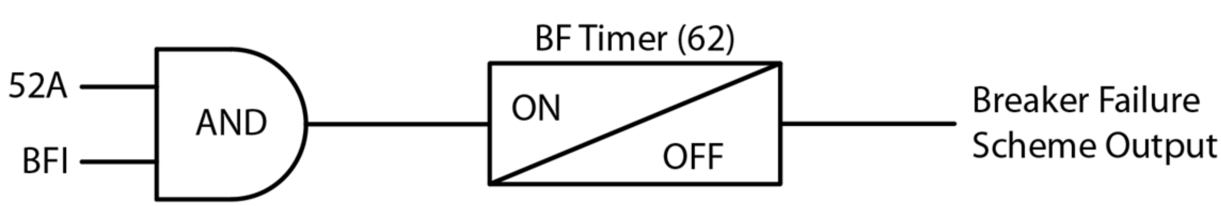


Figure 7: Simple Breaker Fail Logic

Let's look at each of the main Breaker Failure Scheme components in detail:

A) Breaker Status (52A)

The Breaker Failure (BF) Scheme needs to know whether the circuit breaker is open or closed before it can determine if the circuit breaker has failed to open. You might think that the design engineer can simply link the 52A contact from the circuit breaker into the scheme and call it a day, but remember that the BF scheme can trip multiple breakers at once. Breaker Failure schemes are relay testers' greatest nemesis. There are many "famous" relay testers who have unintentionally tripped a BF scheme and can regale you with the chaos created when it happens.

A good transmission engineer would never trust a small piece of plastic, like the 52A contact in a breaker, with something as important as a BF scheme. Therefore, BF schemes typically use phase and/or ground current-detectors to determine if the circuit breaker is open or closed. The breaker is considered closed if the measured current is greater than the current-detector setpoint, regardless of the 52A contact position. The circuit breaker is considered to be open if the current is less than the current-detector setpoint.

Most standards recommend setting the BF current-detectors higher than the normal load current to prevent mis-operations when a fault is not present on the system. A high current-detector setting means that the BF scheme will not open multiple breakers when an accidental Breaker Fail Initiate signal is sent under normal operating conditions, or maintenance testing. However, most current-detector settings I've seen in the field are set to the minimum possible settings, which means they are more sensitive, but less secure.

Most generator Breaker Fail schemes don't use current-detectors. These schemes use the circuit breaker's 52b status contact because a generator's steady state contribution to a fault may be less than the recommended fault detector settings. In fact, circuit breaker (CB) contacts may be used whenever the expected current during a BF condition is less than the recommended fault detector setting. This makes the BF scheme less secure, as many people who have shut down an entire generating plant after racking out a generator breaker during maintenance testing can attest.

The generating plant shut down because the 52b contact opened when the CB was racked-out, which caused a BF Trip. From the relay's perspective:

- The circuit breaker closed because the 52b opened.
- The undervoltage protection turned on because the circuit breaker closed.
- The undervoltage picked up because the generator voltage was lower than its setpoint. (Remember that the generator is offline and stopped for maintenance.)

- The undervoltage timer expired and sent a trip signal to the CB.
- The Breaker Fail Timer started.
- The BF protection operated the Breaker Fail Lockout Relay because the CB remained closed.

All the CBs connected to the "failed" CB opened and isolated the generating station from the rest of the system, and then heads started rolling.

This scenario is exactly why design engineers require current-detectors to determine whether the circuit breaker is open or closed, as shown in Figure 8.

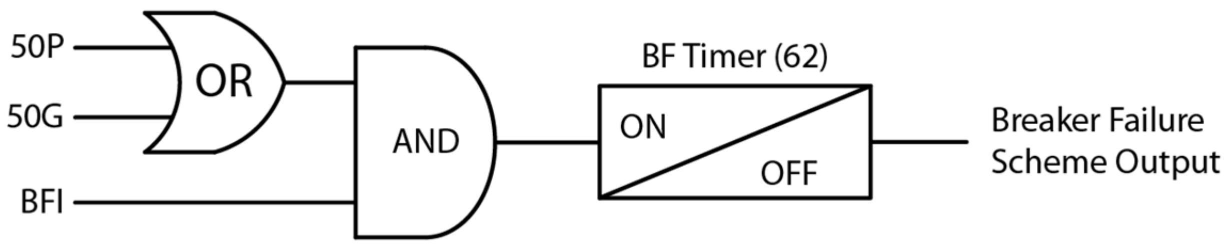


Figure 8: Simple Breaker Fail Logic with Current-detectors

B) Breaker Fail Initiate (BFI)

Any relay, or element inside a relay, that trips the circuit breaker should also send an identical Breaker Fail Initiate signal. Breaker Failure schemes with individual BF relays usually have a Breaker Failure Initiate circuit connected to the BF relay's input(s) that are energized when a trip is sent to the circuit breaker. Manual open commands found in trip circuits are usually not included.

Relays with internal Breaker Failure elements usually have a BFI logic setting that includes every element set to trip the circuit breaker inside the relay. Other relays nearby that also trip the breaker will have a BFI output contact connected to an input in the relay. The BFI setting should also include the inputs from the other relays that trip the CB.

The BFI input should include any protection that should trip the circuit breaker.

C) Breaker Failure Timer

The Breaker Failure Scheme opens several circuit breakers and could cause havoc on the power system if it operates incorrectly. Therefore, the Breaker Failure Timer (62BFTD) delay should be longer than:

- the normal circuit breaker opening time, and
- the time necessary for any arcs to be quenched after the circuit breaker opens, and
- the BF element to detect that the CB is open and disarm itself, and
- a margin of time to account for unexpected circumstances to give the CB plenty of time to operate before all the other circuit breakers are tripped by the BF Scheme.

A typical BFT delay is between 15 and 25 cycles.

4. Testing Breaker Failure Schemes

Testing a Breaker Failure Scheme is pretty simple if you look at it from a power system perspective, instead of digging through all the individual relay nuances. From a power system perspective, the BF-element starts its timer when it detects a trip signal has been sent to the CB, and the CB is still closed after its timer expires. If you want to test a Breaker Failure Scheme: send a BFI signal while the BF-element thinks the breaker is closed and measure the time delay between the BFI and BFT.

We will use the following Breaker Failure Scheme Settings and test-set connections in all the example test plans:

- Phase Current-detector (50BFPP) = 1.0A
- Ground Current-detector (50BFGP) = 0.5A
- Breaker Failure Time (62BFTD) = 15 cycles
- BFI = All Trips and Relay Input101
- Trip = Relay Output101
- BFT = Relay Output102
- 52 Status Simulation = Test-Set OUT1
- Trip From Other Relays = Test-Set OUT2
- Trip Signal from Relay = Test-Set IN1
- Breaker Fail trip (BFT) from Relay = Test-set IN2
- Vnom = The Nominal System Voltage
- Inom = Normal system current, or 0.00 Amps to eliminate residual ground math.
- STND PHROT = The Nominal System Phase Rotation (ABC = 0°, -120°, 120°)

All test plans assume that you have already performed the following tests:

- Determine if the BF Scheme uses contact status or current to determine if the CB is closed. Use a test-set output (OUT1) to simulate the CB status, if required.
- Determine if the BFI signal uses a status input. Connect a test-set output (OUT2) to the required input, if required.
- Connect all the AC inputs used by the relay.
- Perform your standard acceptance tests:
  - Power supply Check
  - HMI display Check
  - Relay Self-test
  - Meter test
  - Pulse all Outputs
  - Verify Inputs operate correctly
- Test all other elements inside the relay.

Here are several different ways to test a Breaker Failure Scheme once all the standard tests have been completed:

A) Manual Testing a Stand-Alone Breaker Failure Relay

Follow these steps to test a Stand-Alone Breaker Failure Relay manually:

- Connect a test-set digital input (IN2) to the relay's BFT output contact (Output102).
- Set up a normal Prefault State with nominal current, nominal voltage, and a closed CB contact (OUT1), if required.
- Set up a Fault State that:
  - Initiates a BFI with test-set OUT2.
  - Injects current greater than the Phase BF Current-detector (50BFPP) settings, and/or keeps the test-set OUT1 contact in the breaker-closed position.
  - Starts a timer that stops when the BFT is detected by IN2.
  - Stops when the BFT is detected.
- Inject the Prefault State for a few seconds.
- Apply the Fault State.
- Compare the Timer setting to the expected time delay (62BFTD). (The expected time is 15.00 cycles compared to the measured time of 15.34 cycles = 2.9% error). Check the relay specifications for the maximum absolute tolerance when dealing with a small number like 15 cycles.

The hardest part of this test is accounting for your test-set's contact closing time. For example, the MTS-5n00's output closes 6ms after the close command is sent. You can add an extra state to account for the contact closing time, as shown below:

Test-Set Channel	1 - Prefault		2 – Close Contact		3 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vnom	STND PHROT	Vnom	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom	STND PHROT	Inom	STND PHROT	1.2 * 50BFPP	STND PHROT	0.000A	N/A
OUT1	52a		52a		52a		52b	
OUT2	Off		On		On		Off	
Max Time	2.0s		Test-Set Contact Closing Time (6ms)		120% * 62BFTD			
Timer1					Start = State 3 Stop = IN2 On			

Figure 9: Stand-Alone Breaker Fail Test with Test-Set Contact Time Removed

The following test plan shows the same plan where the expected time is 62BFTD + Test-set Contact Closing Time + Maximum Tolerance. The actual measured time was 15.78 cycles, including the 6ms test-set OUT1 closing time.

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vnom	STND PHROT	0.00	N/A
I1 / I2 /I3	0.500A	STND PHROT	1.2 * 50BFPP	STND PHROT	0.000A	STND PHROT
OUT1	52a		52a		52b	
OUT2	Off		On		Off	
Max Time	2.0s		120% * 62BFTD			
Timer1			Start = State 2 Stop = IN2 On			

Figure 10: Stand-Alone Breaker Fail Test

B) Manual Testing a Breaker Failure Element Inside a Standard Relay

You can use the previous stand-alone breaker failure relay steps if the BF-element uses a digital input in its BFI settings. Follow these steps to manually test a Breaker Failure Element in a relay with a BFI setting that includes other elements inside the same relay:

- Determine which other protective elements inside the relay initiate a breaker failure.
- Set up a normal Prefault State with nominal current, nominal voltage, and a closed CB contact (OUT1), if required.
- Set up a Fault State that:
  - Applies a realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should operate the trip output (Output101) and initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings. The CB contact should remain closed, if required.
  - Starts a timer that stops when the Trip is detected.
  - Stops the test when the Trip is detected.
- Run the Prefault State for a few seconds and then run the Fault State. Record the trip time (1.49 cycles).
- Change the Fault state to:
  - Start a timer that stops when the BFT is detected.
  - Stops the test when the BFT is detected.
- Run the Prefault State for a few seconds and then run the Fault State. Record the BFT time (16.50 cycles).
- Subtract the Trip time from the BFT time to get the measured Breaker Fail Time Delay (16.50 – 1.49 cycles = 15.01 cycles), which bypasses all the additional time delays included in the Trip tolerance.
- Compare the measured Breaker Fail Time Delay (15.01 cycles) to the 62BFTD setting (15.0 cycles). Is the time delay within the expected tolerance?

You can combine the two test procedures if you can create a timer that measures the time between the Trip and BFT output contact operations with the following modifications:

- Set up a Fault State that:
  - Applies a realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should operate the trip output (Output101) and initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings. The CB contact should remain closed, if required.
  - Starts a timer when the Trip contact operates and stops when the BFT is detected.
  - Stops the test when the BFT is detected.

- Run the Prefault State for a few seconds and then run the Fault State. Record the measured Timer time (14.99 cycles) and compare it to the 62BFTD setting.

The following test plans show the two manual test procedures:

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.000A	N/A
OUT1	52a		52a		52b	
Max Time	2.0s		120% * Trip Time			
Timer1			Start = State 2 Stop = IN1 On			

Figure 11: Manual Breaker Fail Element Test #1

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.000A	N/A
OUT1	52a		52a		52b	
Max Time	2.0s		120% * 62BFTD			
Timer1			Start = State 2 Stop = IN2 On			

Figure 12: Manual Breaker Fail Element Test #2

The following test demonstrates the combined test procedure that merges the two test procedures if your test-set (MTS-5n00, Doble Protection Suite, Megger AVTS, or PowerDB) allows you to create a timer that can start when the Trip contact operates, and stops when the BFT contact operates.

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	**Angle**	**Mag**	**Angle**	**Mag**	**Angle**
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.000A	N/A
OUT1	52a		52a		52b	
Max Time	2.0s		120% * 62BFTD			
Timer1			Start = IN1 On Stop = IN2 On			

Figure 13: Combined Manual Breaker Fail Element Test

C) Dynamic Test for a Breaker Failure Element

Some test-sets don't make it easy to record manual test results, or don't have customizable timers (Doble Protection Suite, Enoserv RTS). This test procedure allows you to dynamically test the Breaker Failure Element using a 5% Under/Over dynamic test technique.

A dynamic test should always start with the 5% over state to prove that your test condition is set up correctly. This test is very similar to the previous BFT test, as per the following steps:

- Determine which other protective elements inside the relay initiate a breaker failure.
- Set up a normal Prefault State with nominal current, nominal voltage, and a closed CB contact (OUT1), if required.
- Set up a Fault State that:
  - Applies a realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings. The CB contact should remain closed, if required.
  - Starts a timer that stops when the BFT is detected.
  - Stops the test when the State 2 Max Time expires, which should be the sum of the 62BFTD (15 cycles) + the max tolerance (Rule of thumb for small numbers = 3 cycles) that equals 18 cycles in our test case.
- Run the Prefault State for a few seconds and then run the Fault State. Record the BFT time (16.50 cycles).
- You now know that the actual 62BFTD is less than your measured Breaker Failure Time delay (16.5 cycles).
- The test conditions between dynamic tests should only have one change to ensure you are testing what you think you are testing. We're testing the time delay, so you should duplicate the previous Fault State and change the State 2 Max Time to the 62BFTD (15 cycles) - the max tolerance (Rule of thumb for small numbers = 3 cycles) for a 12 cycle delay in our test case. You can reduce the tolerance if you wish to gain more accuracy, but the relay may trip if you perform a test within the expected tolerance.
- The evaluation should be changed to expect No Operation.
- Run the Prefault State for a few seconds and then run the Fault State. The BFT should not operate because the 62BFTD timer should not time out within 12 cycles. If this is the case, the 60BFTD is somewhere between 12 – 16.5 cycles. Any number between those two numbers passes, so there is no reason to continue testing if both tests pass.

The following test plans show the two Dynamic test procedures:

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.000A	N/A
OUT1	52a		52a		52b	
Max Time	2.0s		62BFTD + Tolerance			
Timer1			Start = State 2 Stop = IN1 On Expect ≈ 15cycles			

Figure 14: Dynamic Breaker Fail Element Test #1

Test-Set Channel	1 - Prefault		2 – Fault State		Off State	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.00	N/A
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.000A	N/A
OUT1	52a		52a		52b	
Max Time	2.0s		62BFTD - Tolerance			
Timer1			Start = State 2 Stop = IN2 On Expect No Op			

Figure 15: Manual Breaker Fail Element Test #2

5. Testing Breaker Failure Schemes with State Simulations

State simulations allow you to control every aspect of a test, which is why they are my default test procedure. Sometimes the test-set macros can get in the way of realistic fault simulations; like Doble and Enoserv RTS tests that do not inject Prefault values between pulses, or some Manta MTS productivity modes that are missing the channels necessary for complex tests, or Omicron Test Universe's hidden errors that prevent you from running tests. I immediately switch to the following test modes when I realize that a test isn't running the way I want it to, and I find myself in a battle with the test-set software instead of testing relays:

- Doble's Protection Suite State Simulation Test Step
- Enoserv's RTS Logic/Scheme Test
- Manta's Manual Test Menu
- Omicron's Test Universe State Sequencer Test Module

You could use any of these modules to perform the tests in the previous section, but each of these test-sets have different operating characteristics that require slight tweaks to perform a Breaker Failure dynamic pickup/timing test. The following sections detail the specific test-set requirements to build a dynamic test procedure that can be applied to any element in any relay.

A) Doble's Protection Suite State Simulation Testing

Doble's Protection Suite software allows you to set all of the state transitions to move to the next state if the timer expires, or jump to another state if the contact operates. We can create a Postfault state at the end of the test procedure that the test will jump to if the BFT operates in any state.

You can set a timer that starts when the 5% Over Trip State starts, and stops when the relay output operates. The evaluation is set to pass if the timer falls within the timing accuracy of the element. If the element operates in any state other than the Pickup state, the test fails because the timer will be bypassed.

The following test procedure reverses the previous procedures to obtain a Breaker Fail Trip evaluation with one timer:

- Create five States in the State Simulation Test.

- Create a Timer with the following settings:
  - Expected Result/Mode = Value.
  - Expected Result/Time = Expected 62BFTD (15 cycles).
  - Tolerance/Minus/Plus = Relay tolerance + test-set OUT2 closing time, if required (Rule of thumb for small numbers = 3 cycles).
  - Tolerance/Type = Absolute.
  - Start State = 5% Over Trip State.
  - Stop Event/Stop State = LN2 (IN2 / Output 2).
  - Stop Event/Condition = 0 ->1.
- Set a Prefault State with:
  - Nominal current, nominal voltage, and a closed CB contact (OUT1), if required.
  - Maximum Duration = 2.00s, or longer.
  - Trigger = LN2 (IN2).
  - Event = 0 -> 1.
  - Transition To = Postfault State, which will be the last state in the test.
  - Delay = 0.0000s.
  - If the BFT operates in this state, it will jump to the last state and skip all the timers.
- Set a 5% Under No-Op State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings. The CB contact should remain closed, if required.
  - Maximum Duration = 62BFTD (15 cycles) - the max tolerance (Rule of thumb for small numbers = 3 cycles), which would be a 12 cycle delay in our test case.
  - Trigger = LN2 (IN2).
  - Event = 0 -> 1.
  - Transition = Postfault State, which will be the last state in the test.
  - Delay = 0.0000s.
  - If the BFT operates in this state, it will jump to the last state and skip all the timers.
- Set a Prefault2 State with:
  - Nominal current, nominal voltage, and a closed CB contact (OUT1), if required.
  - Maximum Duration = 2.00s, or longer.
  - Trigger = LN2 (IN2).
  - Event = 0 -> 1.
  - Transition To = Postfault State, which will be the last state in the test.
  - Delay = 0.0000s.
  - If the BFT operates in this state, it will jump to the last state and skip all the timers.

- Set up a 5% Over Trip State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings. The CB contact should remain closed, if required.
  - Maximum Duration = 62BFTD (15 cycles) + the max tolerance (Rule of thumb for small numbers = 3 cycles), which equals 18 cycles in our test case.
  - Trigger = LN2 (IN2).
  - Event = 0 -> 1.
  - Transition = Postfault State, which will be the last state in the test.
  - Delay = 0.0000s
  - If the BFT operates in this state, the timer will start and record the BFT time.
- Set up a Postfault State that:
  - applies zero volts and amps for a few cycles to use as a placeholder for the test, or
  - applies the same currents and voltages from the trip state with a Maximum Duration set at the expected CB trip time to give the relay time to display the correct targets, or
  - applies nominal voltage for 30-60 seconds to give you time to review the targets before other elements, like undervoltage, have a chance to operate.
- Run the test. If the BFT operates in any state before the 5% Over Trip State, the test-set will jump to the last state and bypass the timer, which means the test should fail. If the BFT operates in the 5% Over Trip State, the timer should start and record the BFT trip time. If the Timer evaluation passes, you know that the time delay is between 5% Under No-Op State Maximum Duration setting and the measured timer delay. Any number between those two values should be a pass, so your time test is complete.

The following Figure displays the test plan:

Timer Settings

Mode	Time	Minus	Plus	Type	Start State	Input	Condition
Value	62BFTD (18 cy)	Tolerance (3 cy)	Tolerance (3 cy)	Absolute	4 – 5% Over Trip State	LN2	0->1

Test-Set Channel	1 - Prefault		2 – 5% Under No-Op State	
	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT
Maximum Duration	>120 cy		62BFTD – Tolerance (12 cy)	
Time Constant L/R	0.00 cy		0.00 cy	
Trigger	LN2 (IN2)		LN2 (IN2)	
Event	0 -> 1		0 -> 1	
OUT1	52a		52a	
Transition To	Postfault (State 5)		Postfault (State 5)	
Delay	0.00 cy		0.00 cy	

Test-Set Channel	3 – Prefault2		4 – 5% Over Trip State		5 – Postfault	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.0V	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.0A	STND PHROT
Maximum Duration	>120 cy		62BFTD + Tolerance + OUT2 Op Time? (18 cy)		3 cy	
Time Constant L/R	0.00 cy		0.00 cy		0.00 cy	
Trigger	LN2 (IN2)		LN2 (IN2)		N/A	
Event	0 -> 1		0 -> 1		N/A	
OUT1	52a		52a		52b	
Transition To	Postfault (State 5)		Postfault (State 5)		N/A	
Delay	0.00 cy		0.00 cy		N/A	

Figure 16: Dynamic State Simulation Test with Doble State Simulation

B) Enoserv's RTS Logic/Scheme Test

Enoserv RTS' Logic/Scheme Tests can only move forward from one state to the next, and the trigger to the next state can only be a contact or time-out. You can only make one evaluation per input, so you can either split the test into two as described in previous sections, or jumper IN2 and IN3 on the test-set so that the BFT will operate both test-set inputs.

You can build a test with two timers and five states, as per the following description:

- Set a Prefault State with:
  - Nominal current, nominal voltage, and normal phase rotation.
  - Duration (cy) = 120 cy.
  - State to Advance to the next state when this input = Delay Time.
  - Output 1 = a closed CB contact (OUT1), if required.
- Set a 5% Under No-Op State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Duration (cy) = 62BFTD (15 cycles) - the max tolerance (Rule of thumb for small numbers = 3 cycles), which would be a 12 cycle delay in our test case.
  - State to Advance to the next state when this input = Delay Time.
  - Output 1 = a closed CB contact (OUT1), if required.
- Go to User Options to set up a no-operation evaluation on Input 02 to perform one-half of the dynamic test, as per the following instructions:
  - Input Name = BFT
  - Enable on = 5% Under No-Op State
  - Start on = State Inception
  - Stop On = Open -> Close
  - Pass/Fail = Verify NOOP
- Set a Prefault2 State with:
  - Nominal current, nominal voltage, and normal phase rotation.
  - Duration (cy) = 120 cy.
  - State to Advance to the next state when this input = Delay Time.
  - Output 1 = a closed CB contact (OUT1), if required.

- Set up a 5% Over Trip State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Duration (cy) = 62BFTD (15 cycles) + the max tolerance (Rule of thumb for small numbers = 3 cycles), which equals 18 cycles in our test case.
  - State to Advance to the next state when this input = Delay Time.
  - Output 1 = a closed CB contact (OUT1), if required.
- Go to User Options to set up a time evaluation on Input 03 to perform the second half of the dynamic test, as per the following instructions:
  - Input Name = BFT
  - Enable on = 5% Over Trip State
  - Start on = State Inception
  - Stop On = Open -> Close
  - Pass/Fail = Verify Op & Verify Time
  - Expected Op Time = Expected 62BFTD (15 cycles)
  - Tolerance = Absolute tolerance plus test-set OUT2 closing time, if required (Rule of thumb for small numbers = 3 cycles)
- Set up an optional Postfault State that:
  - applies the same currents and voltages from the trip state with a Maximum Duration set at the expected CB trip time to give the relay time to display the correct targets, or
  - applies nominal voltage for 30-60 seconds to give you time to review the targets before other elements, like undervoltage, have a chance to operate.
- Run the test. If the BFT operates in the 5% Under No-Op State, the test-set Input 02 evaluation will fail the Expect NOOP evaluation. If the BFT operates in the 5% Over Trip State, the timer should start and record the BFT trip time. If the Timer evaluation passes, you know that the time delay is between 5% Under No-Op State Maximum Duration setting and the measured timer delay. Any number between those two values should be a pass, so your time test is complete.

The following Figure displays the test plan:

Test-Set Channel	1 - Prefault		2 – 5% Under No-Op State	
	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT
Duration (cy)	>120 cy		62BFTD – Tolerance (12 cy)	
When this input	Delay Time Out		Delay Time Out	
OUT1	52a		52a	

Test-Set Channel	3 – Prefault2		4 – 5% Over Trip State		5 – Postfault	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.0V	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.0A	STND PHROT
Duration (cy)	>120 cy		62BFTD + Tolerance + OUT2 Op Time? (18 cy)		3 cy	
When this input	Delay Time Out		Delay Time Out		Delay Time Out	
OUT1	52a		52a		52b	

User Options Settings

Input Name	Enable On	Start on	Pass /Fail	Expected op Time	Tolerance
5% Under No Op	2 – 5% Under No-Op State	State Inception	Verify NOOP	N/A	N/A
5% Over Trip	4 – 5% Over Trip	State Inception	Verify Op Verify Time	62BFTD (15cy)	Tolerance (3 cy) / +/-

Figure 17: Dynamic State Simulation Test with an Enoserv RTS Logic/Scheme Test

C) Manta's Manual Test Menu Testing

Manta's front panel is like the state simulation programs from other software packages. Any relay contact operation stops the test because all inputs are set to go to a Postfault state by the factory. Postfault is disabled by default, so the test simply stops when an input operates. You could manipulate the settings to mimic any test in this paper that does not use a No Operation evaluation.

A dynamic test runs through a series of States that shouldn't operate the BFT output. If the element operates in any state that should not trip, the test fails because the test stops before the timer has a chance to start. Then a timer starts when the 5% Over Trip State starts and stops when the relay output operates. The evaluation is set to pass if the timer falls within the timing accuracy of the element.

Use the following test plan to create a dynamic manual test using Manta's Manual Test Menu:

- Go to Advanced Settings and change the following settings:
  - Maximum Fault Duration Enabled = cycles
  - Number of Fault States = 4
- Disable the BFT (IN1) contact sensing by removing one wire from IN1, or going to Advanced Settings/Set up I/O and Timers/Configure State Control and changing the #1 Go To State setting to Same State.
- Go to Advanced Settings/Set up I/O and Timers/Configure Timers and Counters to create a Timer with the following settings:
  - Name = BFT
  - Start Event = Fault 3
  - Start When = On
  - Stop Event = Input 2
  - Stop When = On
  - Display Timer in = Cycles
- Choose the correct Fault Type in the Manual Test Menu
- Remove unnecessary information from the screen using the Set up Display Menu
- If circuit breaker status changes are required, go to Advanced Settings/ Set up I/O and Timers/Configure Outputs and:
  - Change #1 Function to Custom
  - Use Configure Custom Output States menu to set the output state, as per the descriptions in each state below.

- Set a Prefault State with:
  - Nominal voltage, nominal current, and phase angles.
  - Maximum Duration = 120.000 cyc, or longer.
  - Output 1 = a closed CB contact (OUT1), if required.
  - If the BFT operates in this state, the test will stop and the timer will not start.
- Set a 5% Under No-Op State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Maximum Duration = 62BFTD (15 cycles) - the max tolerance (Rule of thumb for small numbers = 3 cycles), which would be a 12 cycle delay in our test case.
  - Output 1 = a closed CB contact (OUT1), if required.
  - If the BFT operates in this state, the test will stop and the timer will not start.
- Set a Prefault2 State with:
  - Nominal voltage, nominal current, and phase angles.
  - Maximum Duration = 120.000 cyc, or longer.
  - Output 1 = a closed CB contact (OUT1), if required.
  - If the BFT operates in this state, the test will stop and the timer will not start.
- Set up a 5% Over Trip State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Maximum Duration = 62BFTD (15 cycles) + the max tolerance (Rule of thumb for small numbers = 3 cycles), which equals 18 cycles in our test case.
  - Output 1 = a closed CB contact (OUT1), if required.
  - If the BFT operates in this state, the timer will start and record the BFT time.
- Set up an optional Postfault State that:
  - applies the same currents and voltages from the trip state with a Maximum Duration set at the expected CB trip time to give the relay time to display the correct targets, or
  - applies nominal voltage for 30-60 seconds to give you time to review the targets before other elements, like undervoltage, have a chance to operate.
- Run the test. If the BFT operates in any state before the 5% Over Trip State, the test-set stops before the timer can start, which means the test should fail. If the BFT operates in the 5% Over Trip State, the timer should start and record the BFT trip time. If the Timer evaluation passes, you know that the time delay is between 5% Under No-Op State Maximum Duration setting and the measured timer delay. Any number between those two values should be a pass, so your dynamic test is complete.

The following Figure displays the test plan:

Advanced Settings

- Maximum Fault Duration Enabled = cycles.
- Number of Fault States = 4.
- Advanced Settings/Set up I/O and Timers/Configure State Control and change the #1 Go To state to Same State.
- Advanced Settings/ Set up I/O and Timers/Configure Outputs #1 = Custom

Manual Test Menu Settings

Test-Set Channel	1 - Prefault		2 – 5% Under No-Op State	
	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT
Maximum Duration	>120 cy		62BFTD – Tolerance (12 cy)	
OUT1	52a		52a	

Test-Set Channel	3 – Prefault2		4 – 5% Over Trip State		5 – Postfault	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.0V	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.0A	STND PHROT
Maximum Duration	>120 cy		62BFTD + Tolerance + OUT2 Op Time? (18 cy)		3 cy	
OUT1	52a		52a		52b	

Advanced Settings/Set up I/O and Timers/Configure Timers Settings

Name	Start Event	Start When	Stop Event	Stop When	Display Timers In
BFT	4 – 5% Over Trip State	On	Input 2	On	Cycles

Figure 18: Dynamic State Simulation Test with Manta's Manual Test Menu

D) Omicron's State Sequencer Test

The Omicron Test Universe software requires you to go through all fault states in the order specified. Therefore, you should set the trigger for each state to move forward whenever the time delay is exceeded, or the contact closes, whichever comes first.

Set one Time Assessment to start when the 5% Under No-Op State begins, and to stop when the next state starts. Set the Tnom to be the 5% Under No-Op State time delay with a very small tolerance (+/- 0.001s). The Assessment passes if the relay does not operate. The assessment fails if the relay operates and the test goes to the next state faster than the No-Pickup state time delay. You may be able to use the State Assessment section to create a No Operation evaluation instead.

A second time assessment is set like a traditional time test that starts when the 5% Over Trip State starts, and stops when the relay output operates. The evaluation passes if the timer falls within the timing accuracy of the element. Make sure you enable the test-set IN/BFT sensing via the Hardware Configuration menu for all tests.

You can build a test with two timers and five states, as per the following description:

- Set a Prefault State with:
  - Nominal current, nominal voltage, and normal phase rotation.
  - Use binary trigger condition as specified below = checked.
  - Timeout = Checked & =>120.00 cycles.
  - Input 2 = 1.
  - Bin. Out 1= a closed CB contact (OUT1), if required.
- Set a 5% Under No-Op State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) using the Fault Values Set Mode that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Use binary trigger condition as specified below = checked
  - Timeout = Checked & 62BFTD (15 cycles) - the max tolerance (Rule of thumb for small numbers = 3 cycles), which would be a 12 cycle delay in our test case.
  - Input 2 = 1
  - Bin. Out 1= a closed CB contact (OUT1), if required.

- Go to Time Assessments to set up a no-operation evaluation and perform one-half of the dynamic test, as per the following instructions:
  - Name = BFT No Op.
  - Ignore before = 5% Under No-Op State.
  - Start = 5% Under No-Op State.
  - Stop = 3 – Prefault2.
  - Tnom = 5% Under No-Op State Timeout (12 cycles).
  - Tdev- = 0.5 cy.
  - Tdev+ = 0.5 cy.
- Set a Prefault2 State with:
  - Nominal current, nominal voltage, and normal phase rotation.
  - Use binary trigger condition as specified below = checked.
  - Timeout = Checked & =>120.00 cycles.
  - Input 2 = 1.
  - Bin. Out 1= a closed CB contact (OUT1), if required.
- Set up a 5% Over Trip State with:
  - A realistic fault (the voltage drops, the current magnitude increases, and the current lags by 45-89°) using the Fault Values Set Mode that should initiate a Breaker Fail (BFI). Make sure the test current is greater than the Breaker Fail Current-detector settings.
  - Use binary trigger condition as specified below = checked.
  - Timeout = Checked & 62BFTD (15 cycles) + the max tolerance (Rule of thumb for small numbers = 3 cycles), which equals 18 cycles in our test case.
  - Input 2 = 1.
  - Bin. Out 1= a closed CB contact (OUT1), if required.
- Go to Time Assessments to set up time evaluation to perform the second half of the dynamic test, as per the following instructions:
  - Name = BFT Trip Time.
  - Ignore before = 5% Over Trip State.
  - Start = 5% Over Trip State.
  - Stop = BFT (IN2) 0>1.
  - Tnom = Expected 62BFTD (15 cycles).
  - Tdev- = Absolute tolerance plus test-set OUT2 closing time, if required (Rule of thumb for small numbers = 3 cycles).
  - Tdev+ = Absolute tolerance plus test-set OUT2 closing time, if required (Rule of thumb for small numbers = 3 cycles).

- Set up an optional Postfault State that:
  - applies the same currents and voltages from the trip state with a Maximum Duration set at the expected CB trip time to give the relay time to display the correct targets, or
  - applies nominal voltage for 30-60 seconds to give you time to review the targets before other elements, like undervoltage, have a chance to operate.

Run the test. If the BFT operates in the 5% Under No-Op State, the test-set's BFT No Op evaluation will fail because the time in 5% Under No-Op State would be shorter than the expected time. If the BFT operates in the 5% Over Trip State, the timer should start and record the BFT trip time. If the Timer evaluation passes, you know that the time delay is between 5% Under No-Op State Maximum Duration setting and the measured timer delay. Any number between those two values should be a pass, so your time test is complete.

The following Figure displays the test plan:

Test-Set Channel	1 - Prefault		2 – 5% Under No-Op State	
	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT
Timeout	>120 cy		62BFTD – Tolerance (12 cy)	
Binary Trigger	BFT (IN2) = 1		BFT (IN2) = 1	
OUT1	52a		52a	

Test-Set Channel	3 – Prefault2		4 – 5% Over Trip State		5 – Postfault	
	Mag	Angle	Mag	Angle	Mag	Angle
V1/V2/V3	Vnom	STND PHROT	Vfault	STND PHROT	0.0V	STND PHROT
I1 / I2 /I3	Inom or 0.00A	STND PHROT	Ifault >50BFnn	STND PHROT	0.0A	STND PHROT
Timeout	>120 cy		62BFTD + Tolerance + OUT2 Op Time? (18 cy)		3 cy	
Binary Trigger	BFT (IN2) = 1		BFT (IN2) = 1		Delay Time Out	
OUT1	52a		52a		52b	

User Options Settings

Name	Ignore before	Start	Stop	Tnom	Tdev- Tdev+
BFT No Op	2 – 5% Under No-Op State	2 – 5% Under No-Op State	3 – Prefault2	62BFTD - Tolerance (12 cy)	0.05 cy
BFT Trip Time	4 – 5% Over Trip State	4 – 5% Over Trip State	BFT (IN2) 0>1	62BFTD (15cy)	Tolerance (3 cy)

Figure 19: Dynamic State Simulation Test with Omicron's State Sequencer

6. Testing Breaker Fail Scheme Logic

It has often been argued that there is no reason to test the relay logic if it is simply a copy of an existing scheme. I've found too many errors during maintenance tests to ever subscribe to that policy. Many of those problems essentially disabled the relay and prevented it from tripping the circuit breaker when faults are detected.

One of the errors that stands out was discovered during a maintenance test of a Breaker Failure Scheme. I had replaced all the CT and PT connections with my test-set, connected all operating outputs to my test-set, and simulated inputs with my test-set outputs by connecting them in parallel with the actual inputs. I was testing the Breaker Failure scheme as per the relay settings and everything was working properly because relays will do whatever they are told to do.

However, I happened to notice that another contact was operating during my Breaker Failure tests. It turned out to be a Re-Trip, which sends a last-ditch trip signal to the circuit breaker a few cycles after the initial trip was sent. The relay was programmed to send the Re-Trip, but I realized that its output contact was connected to the Breaker Fail Lockout Relay. The Breaker Fail Scheme was operating perfectly with a 15-cycle delay, but the Re-Trip would always trip the Breaker Fail Lockout in the real world before the Breaker Fail Timer had a chance to operate.

I contacted the utility personnel to report the problem, and they told me that they had just applied a new Breaker Failure Scheme to all their relays. They didn't believe me at first because this scheme had been applied system-wide and *surely someone had tested it thoroughly*. They quickly changed their tune when I was able to get one of them to come on-site to demonstrate the problem. I learned to ALWAYS test the logic after that job.

Relay logic was created to replace physical wiring and relays inside a relay panel, which is why I've always been surprised by the lax attitude about relay logic testing in the industry. Which tests would you perform on a new switchgear installation? I'm hoping that you would do more than trust the point-to-point test from the switchgear manufacturer. A proper test of new switchgear should include a function test using the DC schematics for the switchgear. Your relay testing should also include a functional test of all elements from the equivalent of a schematic drawing.

The relay-logic equivalent of a switchgear schematic would be a version-controlled logic diagram, or a description of operation from the design engineer, or standards and practices for the location. I'm amazed that this documentation isn't required for every relay installation. What would you do if you were told to perform a functional/commissioning test of the switchgear wiring, but they didn't give you any schematics. I hope you would put your foot down and refuse; you should have the same conviction when it comes to relay logic.

A relay logic test is the same as a switchgear schematic test:

- Review the schematic diagram or description of operation.
- Function test each element in each path to operate the relay outputs (Output contacts, LEDs, Front Panel Messages, Virtual Outputs, etc.).
- Make sure that all the functions are appropriate for the location.
- Make sure that everything makes sense.

A) Review the Logic Functions

The following Figure displays the typical Breaker Failure Scheme logic we want to test, which could also be expressed in the math logic used by SEL relays as SV1 = (50P+50G) * (BFI + SV1) and SV1PU = 15 cycles:

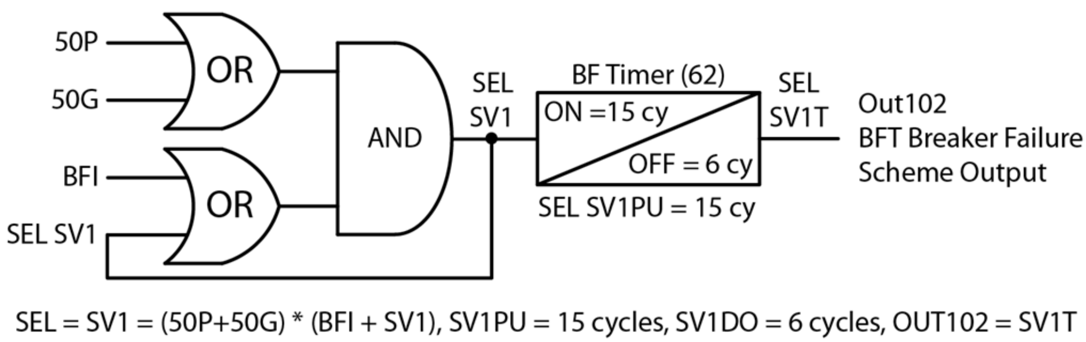


Figure 20: Standard Breaker Failure Scheme Logic

You can convert the logic into a schematic, which should be easier to understand and test. Replace all OR logic gates with contacts in parallel, all AND statements with contacts in series, all Timers with a timer relay, and all outputs with a relay. Figure 21 shows the equivalent schematic of a typical Breaker Failure Scheme:

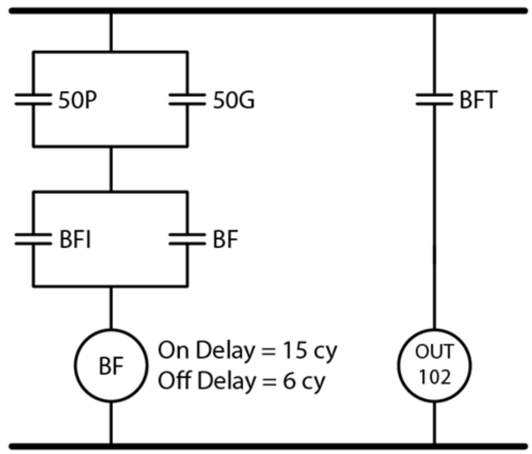
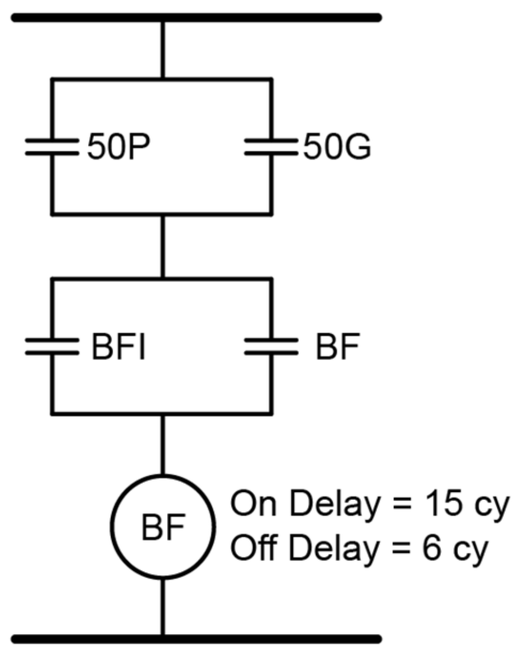


Figure 21: Schematic of Standard Breaker Failure Scheme Logic

How would you test this schematic drawing if it was part of a switchgear/commissioning test where you could touch and feel all of its parts?

Your test procedure might look something like:

- Close 50P and make sure nothing happens.
- Close BFI and the BF relay should start timing and close the BF seal-in contact to keep the BF Scheme energized in case of a chattering contact.
- The BFT contact should close when the BF relay timer exceeds 15 cycles. Out102 should operate.
- Open the BFI contact. Nothing should happen because of the BF seal-in.
- Repeat the above procedure with 50G instead of 50P.
- Measure the time between the 50G opening and the BFT contact opening. It should match the 6 cycle Off Delay.



The last step is to make sure all of this makes sense from a functional perspective. In this case, the top row closes if phase or ground current flows, and the relay thinks the circuit breaker is closed. The timer starts if the BFI closes, and seals itself in to prevent mis-operation due to a chattering trip contact. The BFT occurs 15 cycles later. This is the functionality we were looking for.

You could also expand any logic to include a complete picture of the logic, as shown in Figure 22:

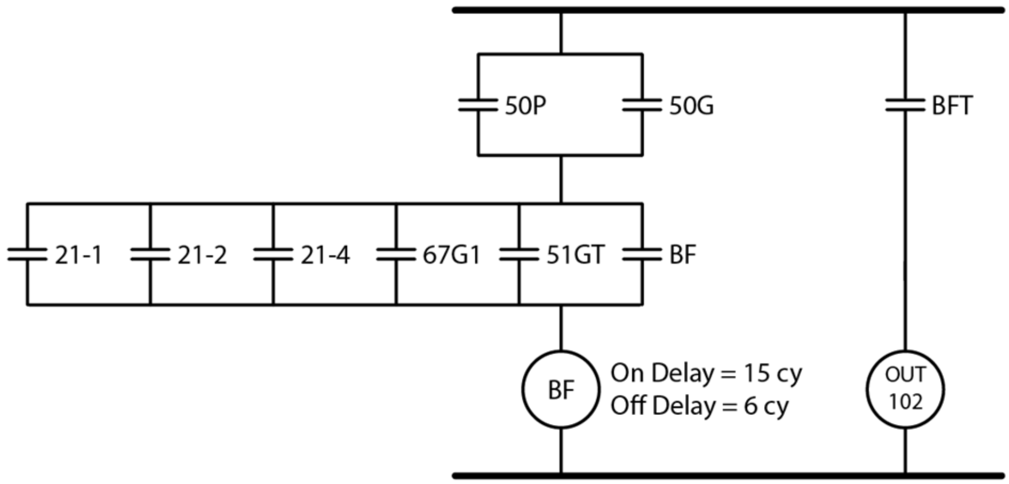


Figure 22: Schematic of Standard Breaker Failure Scheme Logic

B) Test the Logic Functions

It is possible to test this functionality by creating state simulations similar to the previous sections in this paper. The following steps will test the protection using a state for each logical step to prove the BF functionality:

- Create a Prefault state for a few cycles.
- Create a Close Circuit Breaker State:
  - Apply three-phase or phase-phase current higher than the 50P setting longer than the 62BFTD + the relay tolerance.
  - Enable an evaluation that checks to make sure the BFT doesn't operate.
- Inject a BFI Trip State that does not stop when the BFT operates:
  - Check the BFI logic for a non-current element, like Under/Over Voltage or Frequency. If so, create a fault state that operates the BFI. Otherwise, inject a P-P or Three-Phase fault with current higher than the 50P setting.
  - Create an assessment to measure the Trip time.
  - Create an assessment to measure the time between the Trip and BFT.
- Create a Seal-In Check State:
  - Remove the non-current fault or apply nominal voltage and current 5% higher than the 50P setting. The BFI should drop out, but the BF should seal itself in.
  - If the BFI does not drop out, press target reset.
  - Create an assessment that checks that the BFT contact stays closed.

- Create an Off Delay Test State:
  - Lower the current to 5% below the 50P setting. The BFT should open.
  - Create an assessment that measures the time between the start of this state and when the BFT opens.
- Repeat with Phase-Ground currents.

You can add one or two states for any other logic inserted in the Breaker Failure Scheme to make it more secure or selective. You could also do all this testing manually if you do not need the documentation.

Design engineers can add more features into Breaker Fail Schemes and make some pretty complicated logic in their quest to solve more "What if?" questions. You could review the final logic in the relay and work out test scenarios, but I like to simply ask the design engineer "What is this supposed to do?" when the logic is complicated. I use their response to create a test plan that proves that the relay is doing what the design engineer intended it to do, instead of proving that the relay is simply doing what it is told.

Always get as far away as you can from the actual settings when performing relay testing to ensure the relay works as intended instead of as programmed; there is no guarantee that both are the same unless you test it correctly.

7. Conclusion

Relay testing is much easier if you think about the element you are testing from the power system perspective and treat your test-set like a power system simulator. Figure 22 shows a complicated Breaker Failure Scheme that should make any relay tester tremble in their boots.

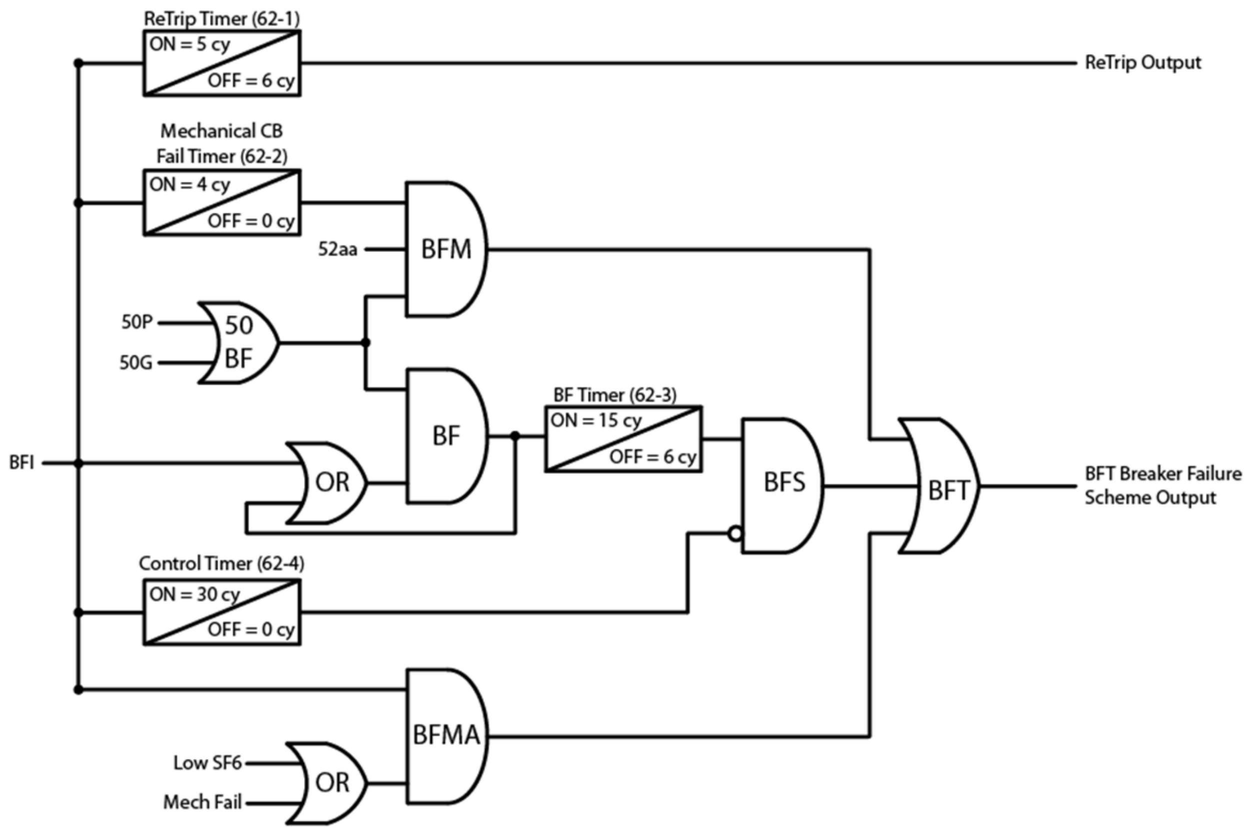


Figure 23: Complicated Breaker Failure Scheme

The SEL equivalent of the same scheme might look like:

- Out101 = Circuit Breaker Trip = TRIP
- Out102 = Breaker Fail Lockout Relay = SV2T + SV3T + SV5
- Out103 = Circuit Breaker Re-Trip = SV1
- In103 = 52aa
- In104 = Low SF6
- In105 = Mech Fail
- SV1 = TRIP
- SV1PU = 5 cy
- SV1DO = 0 cy
- SV2 = IN103 * (50P2 + 50P3) * TRIP

- SV2PU = 4 cy
- SV2DO = 0 cy
- SV3 = (50P2+50G2) * (TRIP + SV1) * SV4T
- SV3PU = 15 cy
- SV3DO = 6 cy
- SV4 = TRIP
- SV4PU = 30 cy
- SV4DO = 0 cy
- SV5 = IN104 + IN105
- SV5PU = 0 cy
- SV5DO = 0 cy

Are your eyes rolling into the back of your head? You could reverse-engineer the relay logic to create a test plan, but the relay will do whatever it is programmed to do. Would you find the three mistakes in the logic if you simply reverse-engineered the settings to test the programmed functionality?

A better approach would be to contact the design engineer and ask them how the Breaker Fail Scheme is supposed to operate. The following description of operation describes the logic:

- If the relay sends a TRIP signal to the circuit breaker and initiates a BFI, a Re-Trip signal will be sent 3 cycles later to trip the circuit breaker via another output contact.
- There is no reason to wait for the full 62BFTD (15 cycles) if we can detect that something is wrong with the circuit breaker mechanism. If the relay detects that the circuit breaker mechanism has started the opening process and the circuit breaker still has not opened within the manufacturer's specified time, we can issue a faster BFT via the following logic (BFM):
  - If the relay sends a TRIP signal to the circuit breaker, AND
  - the mechanism tries to open (52aa contact closes), AND
  - the relay thinks the CB is still closed four cycles later because current is flowing through the circuit breaker higher than the current detector setting (50P2 OR 50G2), then
  - the relay will send a Breaker Fail Lockout Trip to open all the adjacent circuit breakers via a BFT.

- A standard Breaker Failure Scheme is applied with a Control Timer to create a window of operation for the BFT. The Breaker Fail Signal can only be sent within 30 cycles after the BFI is detected to prevent standing trips on the adjacent circuit breakers after the fault has been cleared. The following describes the Breaker Failure Scheme (BFS) operating conditions:
    - If a BFI signal is detected AND current is flowing through the circuit breaker higher than the current detector setting (50P2 OR 50G2), then the BF Timer (62-3) will start.
    - The BFS logic seals itself in if the BFI signal chatters or bounces to ensure the BFS logic keeps running in case of contact failure.
    - The BFS will issue a BFT if the circuit breaker remains closed (Current > 50P2 or 50G2) 15 cycles after the BFI signal as received. The BFS logic resets and open the BFT output after 30 cycles to prevent standing trips on the power system after the event has passed.
- A BFT signal will also be sent if a BFI signal is received and something is wrong with the circuit breaker mechanism or insulation. A BFT trip will be sent with no intentional time delay if:
    - the circuit breaker SF6 Low alarm is received and the relay detects a BFI signal, OR
    - a circuit breaker mechanical alarm is detected and the relay receives a BFI signal.

The following test plans can test each part of the element using a power system perspective:

A) Re-Trip Test Procedure

You can test the Re-Trip Logic with the following test procedure:

- Connect Output103 to IN3 on your test-set.
- Run any of the TRIP timing tests that also issue a BFI.
- Measure the TRIP Time.
- Measure the Re-Trip Time.
- Calculate or measure the difference between the two times.

The test will pass if you only look at the logic or relay settings, but it fails if you look at the description of operation. That is the first mistake in the logic. The time delay does not match the engineer's intent. You can only determine engineer's intent by asking the engineer, or via a description of operation.

B) Mechanical CB Fail (BFM) Test Procedure

You should test this protective function with the circuit breaker. Anything else will be a waste of time because you'll never know if the circuit breaker is sending the correct signals.

- Make sure the 52aa contact is connected to the relay.
- Close the circuit breaker.
- Run any TRIP timing test that also issues a BFI, and stop the test one cycle after the actual trip time. The BFT protection should not have operated.
- Run the same TRIP timing trip test that stops seven cycles after the trip. The BFT protection should have operated in four to seven cycles.
- Block the 52aa contact and run the same TRIP timing trip test that stops seven cycles after the trip. The BFT protection should not operate.

Creating real simulations simplify your test plans and help you figure out if the logic makes sense for the application. Use the in-service equipment whenever possible.

C) Standard Breaker Fail Scheme (BFS) Test Procedure

This scheme is essentially the same as the previous sections, so you can apply any of the previous test procedures. However, they will all fail because of the second logic mistake. The SV3 logic is defined as SV3 = (50P2+50G2)*(TRIP + SV1)*SV4T, but it should be SV3 = (50P2+50G2)*(TRIP + SV1)*!SV4T. A one-character mistake changed the BFS time delay from 15 cycles to 30 cycles, and the Control Timer (62-4) has the opposite functionality from what was intended. The BFT will turn on and stay on after 30 cycles instead of turning on after 15 cycles and turning off after 30 cycles.

You can test the Control Timer by applying any of the BFT tests in the previous section and adding a timer that starts when the BFI is received and stops when the BFT output turns Off.

D) Circuit Breaker Alarm Breaker Failure (BGMA) Test Procedure

The circuit breaker has sensors that sends an alarm if the SF6 inside the circuit breaker is low. The circuit breaker controls will prevent it from opening if the SF6 level is dangerously low. It can also detect problems with the trip and close supply power. Attempting to open a circuit breaker is dangerous if these two problems already exist, so a fourth Breaker Failure Scheme is applied to bypass the Breaker Failure Timer. You can test this scheme with the following procedure:

- Simulate an SF6 low alarm at the circuit breaker. The relay should receive the alarm and nothing should happen.

The BFT would operate if you attempted this test with the provided logic settings because of the third logic mistake. This one was unintentional. I didn't notice it until I reviewed this paper for the third time, and then decided to keep it.

The logic for this scheme is SV5 = IN104 + IN105, but it should be TRIP * (IN104 + IN105). This mistake would cause a catastrophic Breaker Failure Trip when the circuit breaker sent an alarm to warn the operators. This is a perfect example why you should always test the relay logic and make sure it makes sense for the application.

Would you want several circuit breakers to trip because someone opened the Trip Coil #1 DC circuit in a circuit breaker? That is exactly what would happen with this logic. I could test it as is and the relay would perform the function as programmed, but that doesn't make it correct; even if I get all green checkmarks on my test sheet. You are the last line of defense in relay protection. If you don't find a problem during commissioning, it probably won't be found until someone gets hurt, the equipment is damaged, or a power system outage occurs.

Here is the complete BFMA test procedure.

- Simulate an SF6 low alarm at the circuit breaker. The relay should receive the alarm and nothing should happen.
- Run a TRIP timing test that also initiates the BFI. Measure the TRIP and the BFT time. The time delays should be nearly identical.
- Simulate a Mech Fail at the circuit breaker. The relay should receive the alarm and nothing should happen.
- Run a TRIP timing test that also initiates the BFI. Measure the TRIP and the BFT time. The time delays should be nearly identical.
- Clear all the CB alarms. Run a TRIP timing test that also initiates the BFI that stops three cycles after the trip. The BFT should not operate. You could skip this test because you should have already proven this part in your previous tests.

If you start applying the principles in this paper to all of your tests, you'll find that:

- You get a better understanding about the power system.
- You learn more about how your local system functions.
- Your testing time for each relay decreases dramatically.
- You are able to troubleshoot your test plans.
- You find more problems with the relays that help prevent mis-operations and protect you and your co-workers.
- Your day to day life becomes much less stressful. There's no testing task you can't handle.
- People think you are much smarter than you really are and start asking you to write papers and present papers at conferences☺

Happy Testing!

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