Improving Breaker Failure Clearing Times

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Abstract—**As the transmission grid evolves to meet growing energy demands, shorter breaker failure clearing times will be required to address higher fault currents and stability issues. Generation is being added to existing generation sites, increasing the fault currents in key transmission substations. Thermal limits may be exceeded during breaker failure events using traditional breaker failure schemes. Delivering power from new generation sources also pushes the transmission grid closer to stability limits.**

Shorter breaker failure clearing times will be required to minimize damage due to breaker failure events and maintain system stability. A number of factors affect overall breaker failure clearing time, including:

- **Operation of the primary protective relays (distance and differential)**
- **Initiation of the breaker failure relay by the primary protective relays**
- **Open-phase detection by the breaker failure relay**
- **Distribution of breaker failure trip signals to adjacent circuit breakers**
- **Operating time of circuit breakers**

Recent technology advances, including faster protection algorithms, faster output contacts, serial communications, and Ethernet communications, can be used to shorten breaker failure clearing times when the use of faster circuit breakers is insufficient or not possible. The effect of this technology compared to traditional breaker failure schemes is quantified through bench tests of innovative products and systems that can be installed today.

I. OVERVIEW

Protective relays, batteries, communications systems, measurement transformers, dc control circuits, and circuit breakers must work together to protect the power system. Multiple battery systems, measurement transformers, protective relays, dc control circuits, and communications systems are commonly used in critical high-voltage (HV) and extra-high-voltage (EHV) stations for reliable clearing of faults. Because of their physical size and high cost, redundant circuit breakers are rarely used to clear faults for circuit breakers that are slow or fail to open.

Local breaker failure relaying and remote backup protection are commonly used to clear faults with adjacent circuit breakers after the failure of circuit breakers. Security and selectivity are critical to breaker failure schemes because additional unfaulted equipment is de-energized to clear faults. Security and selectivity must be balanced with speed and sensitivity because of thermal and mechanical limits of equipment and for system stability. Local backup breaker failure schemes are widely used in modern power systems operating close to their stability limits because of greater selectivity, greater sensitivity, and faster operation [1].

Fig. 1 illustrates a traditional breaker failure scheme for a simple transmission bus with two circuit breakers. Primary protective relays (21A, 87B, and 21C) trip their respective circuit breakers and initiate the breaker failure relays (50BF1 and/or 50BF2). Each breaker failure relay is associated to a single circuit breaker and trips its own electromechanical lockout relay (86BF1 and 86BF2) to distribute trip signals to adjacent circuit breakers on Bus B and the remote ends of the lines.

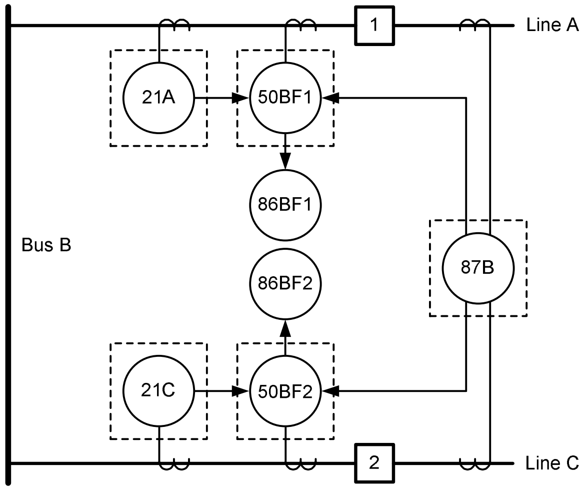

Fig. 1. Traditional breaker failure scheme for simple two-breaker bus

II. BREAKER FAILURE CLEARING TIMES

Shorter breaker failure clearing times are always more desirable when practical. The amount of thermal damage caused by a short circuit is directly related to the duration of the short circuit on the power system.

Large disturbances on a power system, especially faults with breaker failures, reduce the ability to transmit power between generation and load centers. This reduced transmission capacity results in portions of the power system accelerating and decelerating during a fault, increasing the angular distance between the parts of the system. Shorter breaker failure clearing times minimize the angular distance between parts of the system, resulting in a lower chance of an out-of-step condition [2].

Total breaker failure clearing time consists of the following parts:

- Primary relay operate time: time required to initially detect a short circuit on the power system.
- Breaker failure initiate: time required to send an initiate signal from the primary protective relay to the breaker failure relay.
- Breaker failure time delay: time required to clear the fault by the circuit breaker and to detect open phases. An additional margin of 2 or more cycles is usually also added to this time.

- Distribution of breaker failure trip: time to send breaker failure tripping signals to local and remote circuit breakers.
- Circuit breaker clearing time: time required by the local and remote circuit breakers to interrupt the fault current.

Based on Fig. 2, the breaker failure time delay setting is a function of the minimum breaker failure initiate time, maximum circuit breaker clearing time, open-phase detection algorithm, and security margin.

$$\begin{aligned}&\text{Breaker Failure Time Delay} =\\&\text{Maximum Circuit Breaker Clearing Time} +\\&\text{Open-Phase Detection} + \text{Security Margin} +\\&\text{Maximum Trip Output Contact Time} -\\&\text{Minimum Breaker Failure Initiate Time}\end{aligned}\tag{1}$$

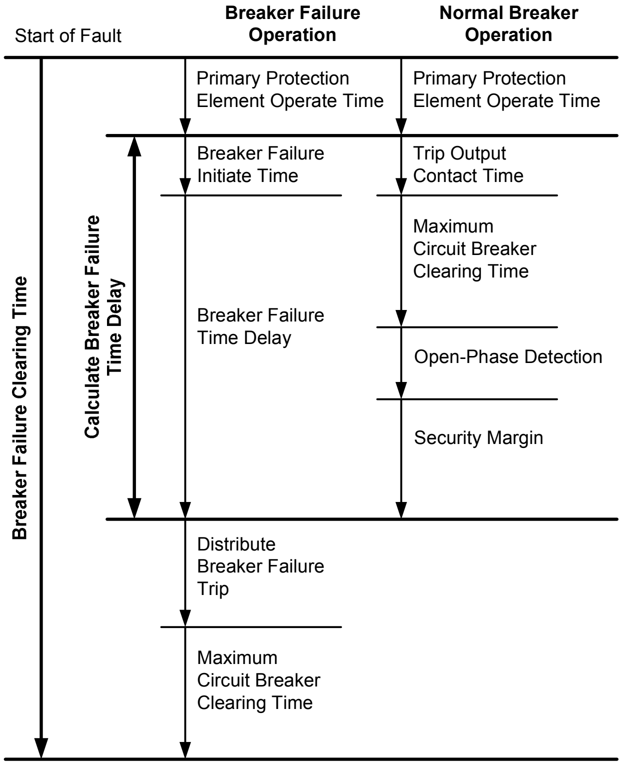

Fig. 2. Breaker failure sequence of events

For a traditional breaker failure scheme with three-cycle circuit breakers, standard output contacts, and overcurrent elements to detect open phases, the minimum breaker failure time delay can be calculated as follows:

$$\begin{aligned}&\text{Minimum Breaker Failure Time Delay} =\\&\quad 3\text{ cycles} + 1.5\text{ cycles} + 2\text{ cycles} +\\&\quad 0.36\text{ cycles} - 0.5\text{ cycles}\end{aligned}\tag{2}$$

$$\text{Minimum Breaker Failure Time Delay} = 6.36\text{ cycles}$$

For security, the minimum breaker failure initiate time is equal to the input debounce timer of the breaker failure relay. The minimum operate time for the breaker failure initiate contact is assumed to be zero, and there are no delays associated with the processing interval of the breaker failure relay.

When calculating the maximum breaker failure clearing time, the maximum breaker failure initiate time must be considered, including primary protection output contact pickup times, debounce timers, and the processing interval of the breaker failure relay. The maximum breaker failure clearing time can be calculated using (3).

$$\begin{aligned}&\text{Maximum Breaker Failure Clearing} =\\&\text{Primary Protection Element Operate Time} +\\&\text{Breaker Failure Initiate Time} +\\&\text{Breaker Failure Time Delay} +\\&\text{Distribution of Breaker Failure Trip} +\\&\text{Maximum Circuit Breaker Clearing Time}\end{aligned}\tag{3}$$

$$\begin{aligned}&\text{Maximum Breaker Failure Clearing} =\\&\quad 1.5\text{ cycles} + 0.36\text{ cycles} + 0.5\text{ cycles} +\\&\quad 0.25\text{ cycles} + 6.5\text{ cycles} + 0.36\text{ cycles} +\\&\quad 1.0\text{ cycle} + 3.0\text{ cycles}\end{aligned}\tag{4}$$

$$\text{Maximum Breaker Failure Clearing} = 13.47\text{ cycles}$$

III. FEATURES OF ADVANCED RELAYS

Direct replacement of primary protective relays with newer, advanced relays reduces overall breaker failure clearing times by reducing the following:

- Primary protection element operate time. High-speed distance elements available in newer relays reduce the maximum operate time for faults from 1.5 to 0.8 cycles in the first 70 percent of Zone 1 elements [3].
- Output contact pickup times. High-speed output contacts reduce trip and breaker failure trip times from 6 milliseconds to under 1 millisecond [3].
- Open-phase detection times. Detecting zero slopes and zero crossing in the current waveforms reduces open-phase detection from 1.5 cycles to under 1 cycle [3] [4].

The overall effect of advanced relays in a traditional breaker failure scheme is equivalent to the effect of faster circuit breakers, as shown in Table I. The combined effect of faster circuit breakers with two-cycle operation times, advanced relays, and high-speed lockout (8 milliseconds) allows breaker failure clearing times as low as 9 cycles.

TABLE I
COMPARISON OF BREAKER FAILURE CLEARING TIMES

	Traditional Scheme		**Traditional Scheme With Two-Cycle Circuit Breakers**		**Traditional Scheme With Advanced Relaying**		**Traditional Scheme With Two-Cycle Circuit Breakers and Advanced Relaying**	
	cycles	**ms**	**cycles**	**ms**	**cycles**	**ms**	**cycles**	**ms**
Primary Protective Relay Data								
Maximum Distance Relay Operate Time 70% of Zone 1 Reach, SIR = 1	1.500	25.00	1.500	25.00	0.800	13.33	0.800	13.33
Trip Output Contacts	0.360	6.00	0.360	6.00	0.060	1.00	0.060	1.00
Breaker Failure Initiate Output Contact	0.360	6.00	0.360	6.00	0.060	1.00	0.060	1.00
Circuit Breaker Data								
Maximum Circuit Breaker Clearing	3.000	50.00	2.000	33.33	3.000	50.00	2.000	33.33
Breaker Failure Relay Data								
Open-Phase Detection	1.500	25.00	1.500	25.00	1.000	16.67	1.000	16.67
Security Margin	2.000	33.33	2.000	33.33	2.000	33.33	2.000	33.33
Breaker Failure Relay Input Debounce Timer	0.500	8.33	0.500	8.33	0.250	4.17	0.250	4.17
Breaker Failure Relay Processing Interval	0.250	4.17	0.250	4.17	0.125	2.08	0.125	2.08
Breaker Failure Pickup Delay	6.500	108.34	5.500	91.67	5.875	97.92	4.875	81.25
Breaker Failure Output Contact	0.360	6.00	0.360	6.00	0.060	1.00	0.060	1.00
Lockout Relay Data								
Lockout Operate Time	1.000	16.67	1.000	16.67	0.500	8.33	0.500	8.33
Local and Remote Circuit Breaker Data								
Maximum Circuit Breaker Clearing	3.000	50.00	2.000	33.33	3.000	50.00	2.000	33.33
Maximum Breaker Failure Clearing Time	**13.470**	**224.51**	**11.470**	**191.17**	**10.670**	**177.83**	**8.670**	**144.49**

IV. ROLE OF COMMUNICATION

Because of the number of relays and circuit breakers involved in clearing a fault during a breaker failure condition, wiring required for breaker failure initiation and breaker failure tripping becomes complicated, as shown in Fig. 3. Wiring becomes further complicated in breaker-and-a-half and ring bus arrangements because multiple breaker failure relays must be initiated by each primary protective relay, as shown in Fig. 4.

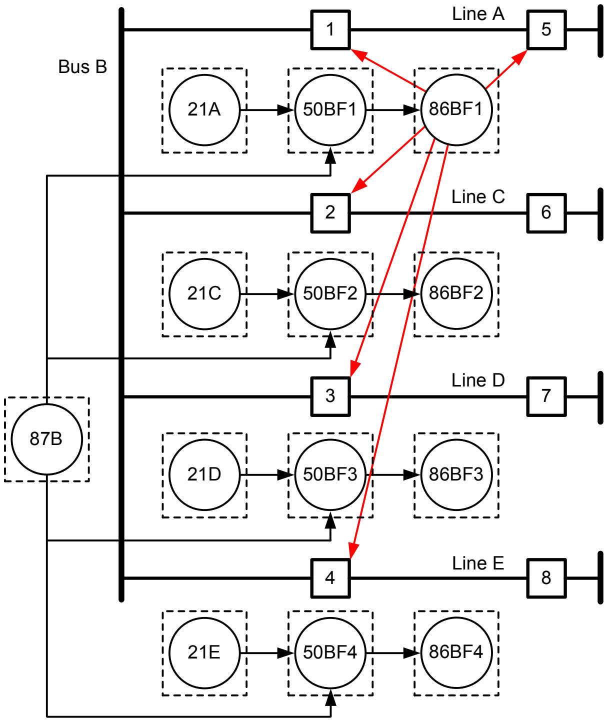

Fig. 3. Hard-wired connections for breaker failure in simple bus arrangements

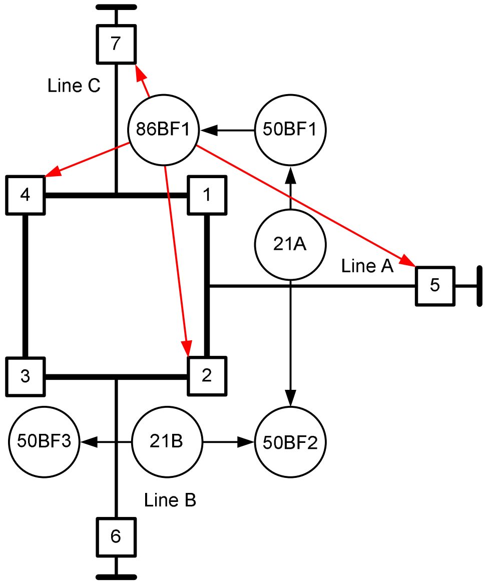

Fig. 4. Hard-wired connections for breaker failure in ring bus

Serial- and Ethernet-based relay-to-relay communications in combination with multifunction protective relays with integrated breaker failure can significantly reduce physical wiring, as shown in Fig. 5. Breaker failure initiate signals and breaker failure tripping signals can be passed between relays without additional wiring.

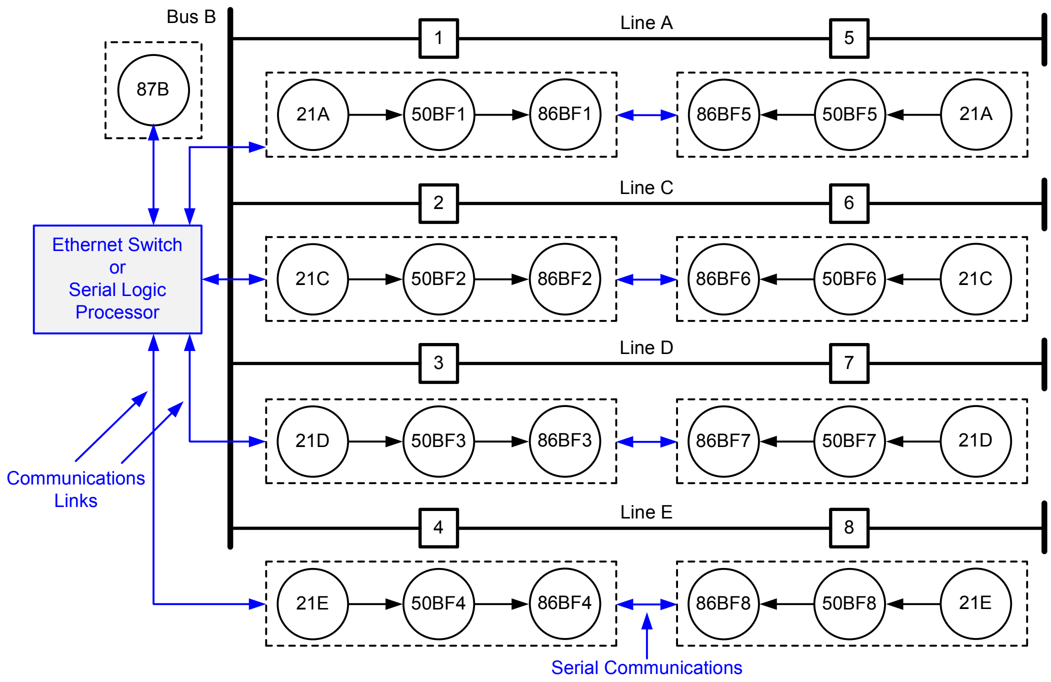

Fig. 5. Reduced physical wiring using relay-to-relay communications

Special care must be taken in calculating the breaker failure time delay and maximum clearing time when communications are used for breaker failure initiation.

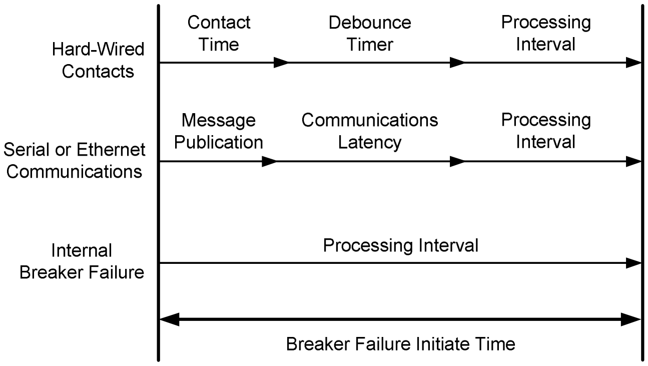

Fig. 6. Methods of breaker failure initiation

Predictable, consistent communications latencies of proprietary, serial, EIA-232-based point-to-point links allow simple calculation of breaker failure initiate and maximum clearing times. Unfortunately, Ethernet-based relay-to-relay communications such as IEC 61850 GOOSE are not as predictable and consistent. As a shared resource, Ethernet network communications latencies will vary based on the size of the network, routing of the messages, and loading of each link at any given time. Implementations of peer-to-peer applications, such as breaker failure, have been observed to vary from 4 to 18.3 milliseconds on quiescent Ethernet networks via IEC 61850 GOOSE because of differences in vendor implementations [5]. Newer relay technologies with best-in-class GOOSE performance for this specialized protection function perform the application in 2 milliseconds.

Because of these large variations, breaker failure pickup delays cannot be adjusted to account for communications latency on IEC 61850 GOOSE-based systems. Careful testing of fully loaded Ethernet networks is required to determine the maximum breaker failure clearing times. For power systems with short critical clearing times, serial EIA-232-based point-to-point links or small, lightly loaded, isolated Ethernet networks are recommended. It is further recommended that message prioritization and segregation be used in managed Ethernet networks via IEEE 802.1p and IEEE 802.1q, respectively.

The test configuration used to gather performance data is shown in Fig. 7. Measurements of breaker failure clearing times minus circuit breaker clearing times were taken using hard-wired contacts from the relays to the test set. Breaker failure initiate times were measured by reviewing time-synchronized relay Sequential Events Recorder (SER) reports in the two relays.

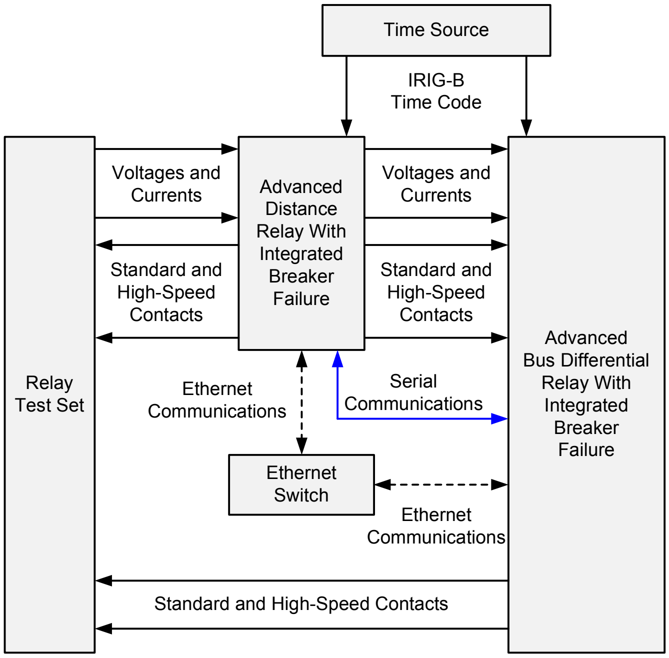

Fig. 7. Test configuration to measure breaker failure initiate times

Table II shows that the use of internal breaker failure tripping may reduce overall clearing times by 5 to 10 milliseconds. It does this by eliminating debounce timers and output contact pickup times associated with transferring statuses between relays using contacts.

TABLE II
PERFORMANCE COMPARISON OF STANDARD AND HIGH-SPEED OUTPUT CONTACTS USED WITH INTEGRATED AND SEPARATE BREAKER FAILURE RELAYS

	Initial Trip (ms)		**Breaker Failure Pickup Setting (cycles)**	**Internal Breaker Failure Trip (ms)**		**External Breaker Failure Trip (ms)**	
	Average	**Maximum**		**Average**	**Maximum**	**Average**	**Maximum**
Advanced Distance Relay High-Speed Output Contacts	13.1	14.3	5.25	101.3	101.5	106.1	106.5
Advanced Distance Relay Standard Output Contacts	16.2	17.3	5.5	107.6	108.3	116.9	117.5

Using high-speed output contacts or communications links has the potential to reduce the breaker failure initiate times by 3 to 6 milliseconds, as shown in Table III. Performance with serial communications and Ethernet IEC 61850 GOOSE messages was similar to the performance of the high-speed output contacts. Note that the IEC 61850 GOOSE times are based on the use of just a single, lightly loaded, unmanaged Ethernet switch. Using different vendor implementations of the IEC 61850 GOOSE protocol and larger networks will likely increase these times.

Based on the speed shown in Table III, the use of serial- and Ethernet-based communications to distribute breaker failure tripping signals to other multifunction digital relays in the substation will eliminate lockout relays, reduce wiring, and further reduce breaker failure clearing times by 4 to 8 milliseconds.

TABLE III
BREAKER FAILURE INITIATE TIMES

	Standard Output Contacts (ms)	**High-Speed Output Contacts (ms)**	**Serial EIA-232 (ms)**	**Ethernet IEC 61850 GOOSE (ms)**
Average	7.6	3.1	1.9	3.4
Maximum	9	4	3	4

V. ADJUSTMENTS TO BREAKER FAILURE DECLARATION TIME

Fast fault detection, tripping, breaker failure detection, and transfer tripping are usually the main considerations of maintaining stability during a breaker failure event. Another consideration needs to be the required speed of the breaker failure system. If we consider the basic power transfer/stability curve shown in Fig. 8, we can see how different factors interact in assessing stability.

As seen in Fig. 8, there are several different factors that can vary the time that makes up the critical clearing time and thus the breaker failure declaration time. These include the power angle at the time of operation and the transfer capability of the initial system, the faulted system, and the recovery system.

A traditional breaker failure system must consider a worst-case scenario to set the breaker failure time. While this worst-case time may be met by using techniques outlined elsewhere in this paper, it may be better if the breaker failure time can be set longer. There are several conditions that may delay clearing but do not require breaker failure tripping [6]. If the breaker failure declaration time is shorter than any of these delays, the breaker failure tripping initiated at all points feeding the fault will almost certainly cause severe system stress. These delays can be caused by a slow circuit breaker, a slow circuit breaker auxiliary switch, remnant flux in the CT (current transformer) circuit, or other nonbreaker failure. While some of the algorithms and techniques discussed in this paper can mitigate some of these problems, it is advantageous to use more time for tripping if it is available without impacting stability.

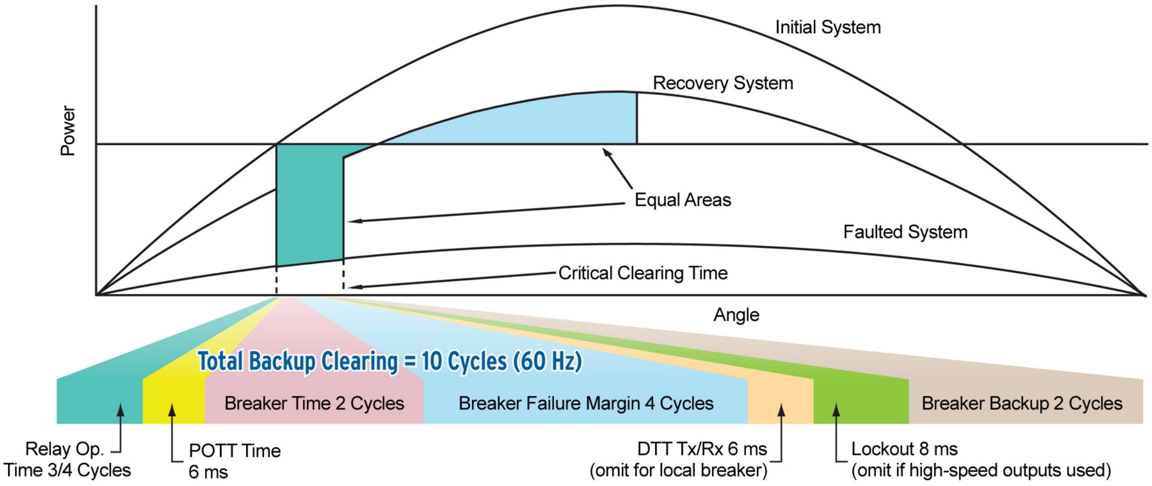

Fig. 8. Power transfer curve showing equal area conditions

The protection engineer is left with two basic issues to resolve: how to determine that a longer breaker failure time can be used and how to input the time change into the scheme settings. Referring again to Fig. 8, the information that can be used to determine if the system can withstand a longer breaker failure time is the prefault load angle and the power transfer capability of the initial, faulted, and recovery systems. The prefault load angle can be accurately measured by relays that include synchronized phasor measurements (synchrophasors). Using direct, relay-to-relay communication of real-time phase angle, the protective relay has a direct input from the relay at the other end of a protected line of the prefault load angle, as shown in Fig. 9. This information can be sent using IEEE C37.118 protocol at rates of up to 60 messages per second. This is far faster than the load angle would change because of normal power system conditions, making it a suitable system to communicate stability limits.

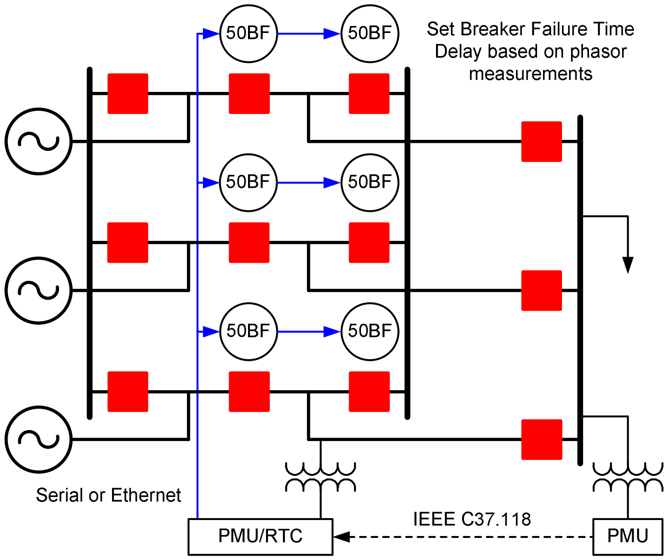

Fig. 9. Load angles are measured and used to set breaker failure time delays

Local and remote information from circuit breaker auxiliary switches can be used to determine the power transfer capability following a system fault. For example, if three lines were in service out of a generating station, the power transfer capability is greater following a fault on one line than if only two lines were in service. High-speed communications using either relay-to-relay serial links or IEC 61850 Ethernet messages will communicate system topology information to allow the relay to determine the need for very fast, or only moderately fast, breaker failure times.

Depending on the power system topology, relying on the circuit breaker auxiliary switches to determine power transfer capability may require several data points at many substations. Using the prefault load angle as shown in Fig. 9 reduces the number of data points to consider and simplifies the logic required to set the breaker failure time settings.

Dynamically changing relay breaker failure time settings introduces test and modeling problems; however, changing the settings group to one that was predetermined and tested is more practical. The conditions to change the settings group to one with a longer breaker failure time are set with simple combinations of lines in service and prefault loading.

Security benefits are demonstrated in the two scenarios illustrated in Fig. 10. In low load conditions with greater stability margins, longer breaker failure time settings allow a generator, line, or bus to remain in service in the event a circuit breaker is slow to clear a fault on the line. In high load conditions, short breaker failure times are used to clear the fault, preventing instability.

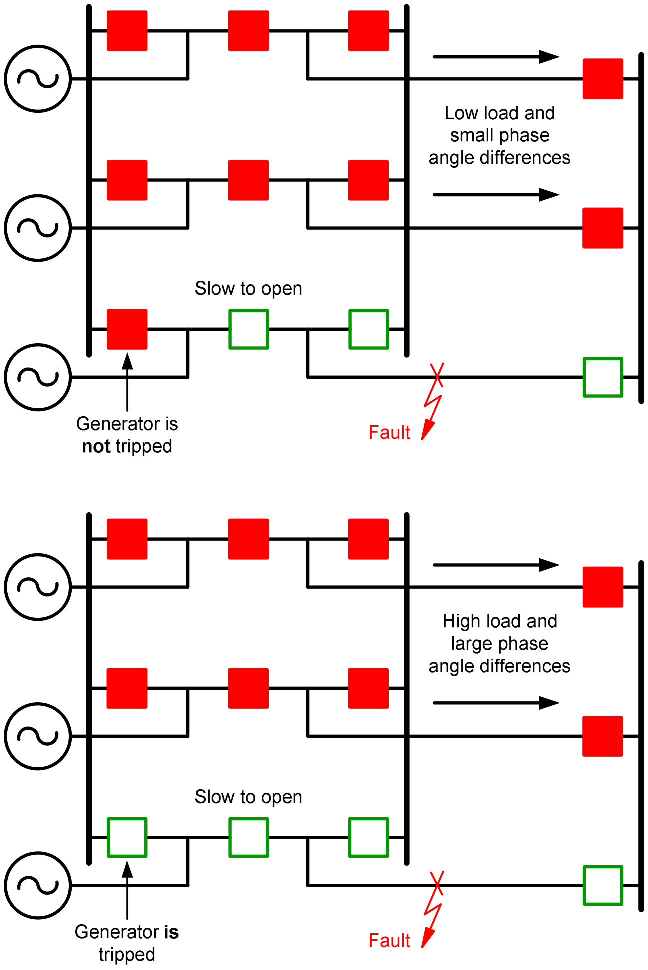

Fig. 10. Longer breaker failure tripping is used under light load conditions for security in case of slow circuit breakers

VI. CONCLUSIONS

Shorter overall breaker failure clearing times are a necessity as generation capacity is increased at existing generation sites and the transmission grid is pushed closer to stability limits. The following must be considered to implement the best-performing and most cost-effective breaker failure schemes:

- Using high-speed algorithms and contacts in advanced relays provides similar performance to faster circuit breakers. In existing substations and generation switchyards, direct replacement of relays with newer, advanced protective relays may be more cost-effective than replacing three-cycle circuit breakers with two-cycle circuit breakers.
- Use of multifunction distance and differential relays with integrated breaker failure protection reduces breaker failure clearing times and eliminates the need for dedicated breaker failure relays.
- Serial and Ethernet communications reduce physical wiring and breaker failure clearing times.
- Consider only using the shortest breaker failure time for conditions when stability is compromised by high load angles or lines out of service. For other conditions, use a longer breaker failure time to reduce the chances of a false declaration.

VII. REFERENCES

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VIII. BIOGRAPHIES

Edsel Atienza received his BSEE from the University of Idaho in 2001. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as an international field application engineer. In 2006, he joined Tampa Electric as a substation operations engineer responsible for all relay testing and maintenance. He returned to SEL in 2008, serving the southeastern United States as a field application engineer.

Roy Moxley has a BSEE from the University of Colorado. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2000 and serves as marketing manager for protection products. Prior to joining SEL, he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the State of Pennsylvania and has authored numerous technical papers presented at U.S. and international relay and automation conferences. He also has a patent for using time error differential measurement to determine system conditions.

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