Using Temporal Causal Models to Isolate Failures in Power System Protection Devices

Nagabhushan Mahadevan, Abhishek Dubey, Ajay Chhokra, Huangcheng Guo and Gabor Karsai

Smart Electric Grids and their underlying generation, transmission and distribution systems are constantly exposed to dynamic environments resulting from varying power flows, both direction and magnitude, changing operational requirements and conditions, physical component degradation, and software failures. Maintaining reliability of the power grid even in the presence of faults is one of the top national priorities [1]. Recent blackouts and Hurricane Sandy in 2012 demonstrated the grid vulnerability and reasons to look at existing defense mechanisms more closely.

State of the art relies on a network of protection devices that include relays to detect anomalies and circuit breakers to isolate parts of the system that include the faulty components. These local protection schemes operate in short timescales to arrest the fault propagation and protect the remaining system. While the protection devices can mask the fault effects locally, it is important to analyze the events in a global context to improve the decision making. Protection malfunction and its correlation with major blackouts require a careful rethinking of its system-wide effects [2], [3]. This problem is often compounded due to loss of information from relays or Remote Terminal Unit (RTU) failure in the field. Such hidden (unobservable) relay failures are hard to locate and may be responsible for cascades [3].

A recent investigation by North American Electric Reliability Corporation (NERC) demonstrated that nearly all major system events, excluding those caused by severe weather, have had relay or automatic control misoperation (almost 2000 in one year), contributing to failure propagation [4]. For example, distance relays, a common protection device used in transmission systems, have been known to incorrectly initiate tripping when impedance falls into the zone settings of line relays caused by heavy load and depressed voltage conditions [2]. The lack of capability for a timely and accurate diagnosis, combined with the potential side-effects of automated protection actions, lead to impending fault cascades which can be avoided [5].

Understanding faults, their causes, and their potential cascades in Electric Grids requires us to consider the effect of protection system failures. This paper describes a modeling formalism and related algorithms that can be used to perform the timely diagnosis and prognosis of failures caused by misoperation of protection systems and automatic controls using available information from the physical and the cyber components of this system.

Our approach is to use a discrete event model that captures the causal and temporal relationships between failure modes (causes) and discrepancies (effects) in a system, thereby modeling the failure cascades, while taking into account propagation constraints imposed by operating modes, protection elements, and timing delays. The key idea in our work is to consider the physical and logical connections of the subsystems and the time required for a fault to propagate from one component to another using temporal causal diagrams (TCD).

Temporal Causal Diagrams (TCD) can model the effects of faults and protection mechanisms as well as incorporate fine-grain, physics-based diagnostics into an integrated, system-level diagnostics scheme. The uniqueness of the approach is that it does not involve complex real-time computations involving high-fidelity models, but performs reasoning using efficient graph algorithms based on the observation of various anomalies in the system. This approach differs from existing practice where fault analysis and mitigation are dependent on a logic-based approach that relies on hard thresholds and local information, often ignoring system-level effects introduced by the distributed control algorithms.

An advantage of modeling the system as a composition of the TCDs of the constituent components is the ability to either generate a model or configure a pre-modeled

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template in external simulators. Such simulators can then be used to study the failure progressions and the cascade dynamics. This paper describes TCDs and their use for simulation to study failure propagation.

The paper is organized as follows: The next sections deal with the related research, the TCD modeling formalism, and modeling a TCD for a segment of a power transmission system. Subsequently, we discuss the translation of the TCD model to build a discrete-event simulation model and follow with results and event-traces for a couple of demonstrative single and multi-fault scenarios. The conclusion discusses the future direction of work.

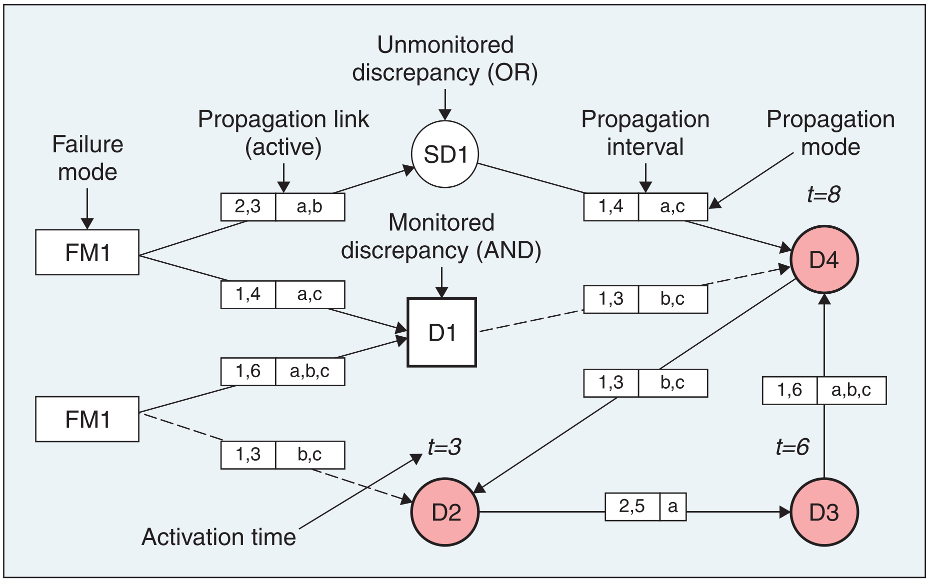

Fig. 1. A simple timed failure propagation graph (TFPG) model [23].

Related Research

A number of approaches exist towards fault diagnostics in power systems domain [6]. These approaches can be classified into Bayesian Approach [7], [8], rule-based reasoning [9], [10], expert systems [11], [12], fuzzy-logic based methods [13], [14], Genetic Algorithm, search based techniques [15], artificial neural network [16], [17], and Petri Nets by abstracting the power system as a discrete event system [14], [18].

A pioneering paper [19] reports a rule-based or logic-based system for location of line faults based on real time information acquired at the control center of a power system. In [6], authors compiled a comprehensive survey of the fault diagnostics systems developed using various knowledge-based techniques. Model-based approaches based on logic behaviors of the protection devices are identified as valuable tools for fault analysis. The on-line alarm analyzer reported in [20] incorporates the cause-effect principles of protective devices into logic-based, proof-oriented algorithms for the analysis of malfunctions. Cause-effect models are used for fault diagnostics of substations in [21]. Upon field-testing with real world data it was found that the proofs are difficult when uncertainties cannot be resolved. The proof algorithm in [20] had to be generalized in order to evaluate the credibility of potentially large number of hypotheses [21].

Our approach is unique in that it models the physical aspects of the system, and at the same time it is able to capture the failures in the cyber components of the system as shown in our prior work [22]. It allows us to consider the physical and logical connections of the subsystems and the time required for a fault to propagate from one component to another. That is, we can capture the salient attributes of the fault propagation without explicitly modeling the complexities of an electrical network. As a result, we arrive at a flexible, yet computationally efficient fault propagation model.

Temporal Causal Diagrams

TCDs are a refinement of our prior work in the field of model-based fault diagnostics, especially Timed Failure Propagation Graphs (TFPG) [5]. The classical TFPG model is a discrete-event model that captures the causal and temporal relationships between failure modes (causes), observable as well as unobservable discrepancies (effects) in a system, and the propagation of failure effects (along with their temporal and modal constraints) from a Failure Mode or a Discrepancy to one or more Discrepancies. In this model, alarms capture state deviations from nominal values. The set of all observed deviations corresponds to the monitored discrepancy set in the TFPG model. Propagation edges, on the other hand, correspond to causality (for example, as defined by energy flow) in the system dynamics. Due to the dynamic nature of the system, failure effects take time to propagate between the components. The delay in general depends on the system's time constants as well as the size and timing of underlying failure. Fig. 1 shows a simple TFPG Model.

However, this modeling formalism does not allow one to capture the behavior and operation (and incorrect, faulty operation) of the built-in autonomous local protection units and the effect of these operations (that can be nominal or faulty) on the fault propagation through the system. These details are critical for the correct diagnosis of the faults in the system and its protection units. While the semantics of the traditional discrete fault models such as TFPG could be stretched to include the operations (commands) and their effects on the system (state) as observed Discrepancies. However, it would be hard to accurately and succinctly model all the required temporal and fault aspects of the protection units and their combinations due to the explosion in the possible failure propagation paths.

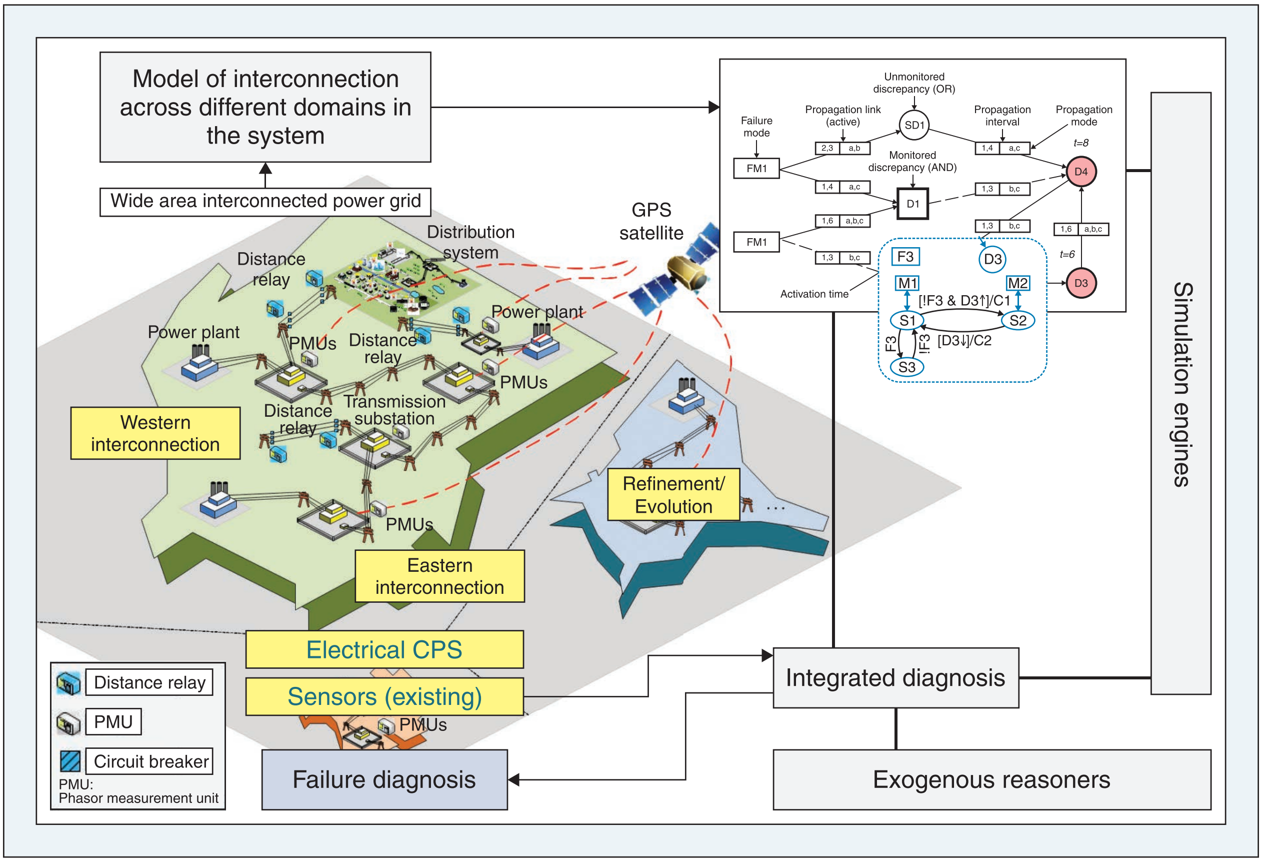

Fig. 2. The integrated system provides the ability to capture failure dynamics along with component behavior. This can be used to simulate behavior for analysis as well as perform online diagnosis, which can integrate exogenous reasoners and use simulation results for disambiguation. CPS refers to Cyber Physical Systems [23].

We model faults and their propagation in a TCD model using TFPG. Nominal and faulty operations of the components (controllers, protection devices, etc.) are captured as Timed Discrete Event Systems (TDES). Models also capture the cascading effects of such behaviors, including their impact on the failure propagation through internal mode changes. The TCD models of each component can be composed together to build the TCD model of the subsystem or system. The integrated TCD model represents faults and their propagation (like the TFPG), the nominal and faulty responses of all components (including controllers, etc.), and the cumulative and cascading effects of these interactions. This approach lends itself to a natural, multi-level reasoning scheme, wherein an exogenous tool can analyze a component or sub-system. The lower level model could work on refining their precise description of the fault, while the higher-level model could work on the causal effect of this fault (i.e., what functionalities are affected by the same). The higher-level reasoner with its abstract model could work much faster to provide a rapid but abstract result that can be refined later. Fig. 2 shows the integrated approach for analyzing power system segments using TCD models.

A TCD model contains TFPG models to represent faults and their propagated effects (anomalies) in the physical and the protection system. The component behaviors (both nominal and faulty) are represented as timed discrete event systems (TDES). The TCD graph model is characterized as follows:

- Q: The set of discrete states of the component.
- F: The set of failure modes, which are the fault causes. Failures modes are not directly observable.
- D: The set of discrepancies, i.e. off-nominal conditions that are the effect of the failure modes.
- E: The set of directed labeled edges that represent the failure-effect propagation from the failure mode and/or discrepancy nodes to other discrepancy nodes.
- M: The set of system/ component operating modes.
- ET: E → I is a map that associates every edge in E with a time interval $[t_1, t_2] \in I$.
- EM: E → P(M) is a map that associates every edge in E with a set of modes in M.
- DC: D → {AND, OR} is a map defining the class of each discrepancy as either AND or an OR node.
- DS: D → {A, **I**} is a map defining the monitoring status of the discrepancy as either A for the case when the discrepancy is active (monitored by an online alarm) or **I** for the case when the discrepancy is inactive (not monitored).
- Σ: The set of events that correspond to controller commands, actuation, external mode commands, detection of the physical state of component, discrepancy detection or other internal events. The presence/

detection of a discrepancy, d, is written as d, while !d relates to the absence/ remission of a discrepancy.

- δ is a transition map between the states of the behavioral model. The transitions are written as [Guard] Event(delay)/Actions. The Guard condition can represent the presence of a local fault $f \in F$ and/or discrepancy $d \in D$. Actions result in production of events that can be communicated to the rest of the system. Delay, if present declares the time after which transition will occur.
- A mode map, $M: Q \rightarrow 2^M$ captures the effect of a state in Q on the TFPG-mode in M. Thus, the system being in a discrete state affects the current modes of the TFPG, which in turn affects the propagation link.

The TCD model of a system (or subsystem) captures the interaction between the TCD models of the individual components. The interactions across component boundaries include failure propagation (as in TFPG), event propagation between the behavioral models (event generation and consumption paradigm), and interactions between the failure propagation and the behavioral models.

The interaction between the failure propagation and behavioral models in a TCD revolves around updates associated with any of the failure modes, discrepancies, and modes. The behavioral model can react to the updates represented in the form of events (appearance, disappearance, change) and or conditions (presence, absence). Likewise, the behavioral model can update the state of the discrepancies and modes, thereby affecting the failure propagation.

Example

Consider the TCD model of a system with three components shown in Fig. 3. Comp1 and Comp3 capture the failure propagation model. Failure modes F1 and F2 are the root causes of failure and their effect propagates through the components and triggers discrepancies D1, D2, D3, D4, D5 and D6. The labels (M1, M2) on some of the failure propagation links indicate the modes in which the link is enabled, thereby allowing failures to propagate. Links without any labels allow fault propagation in any mode. The TCD model captures the behavior of component Comp2. States S1 and S2 are mapped to the system modes M1 and M2. The transitions between the states are governed by the presence and/or absence of the failure mode F3 and discrepancy D3. Discrepancy D3 would be triggered by the presence of failure mode F2. The reaction of Comp2 to the presence of discrepancy D3 (in the absence of F3) is represented by the state transition from state S1 to S2. The model also captures the reaction of the component when discrepancy D3 disappears. The operation state of the component changes from S2 to S1 (guard condition: !D3), and a command is issued (action: C2). If the fault F2 were to reappear and trigger discrepancy D3, component Comp2 would react again to arrest the fault propagation. F3 represents an internal failure in the Comp2. The behavioral model shows that in the presence of fault F3, the components operation state switches to S3, where it is incapable of reacting to the presence of discrepancy D3. However, when the fault F3 disappears, Comp2 resets back to the nominal state S1 and can react to the presence of discrepancy D3.

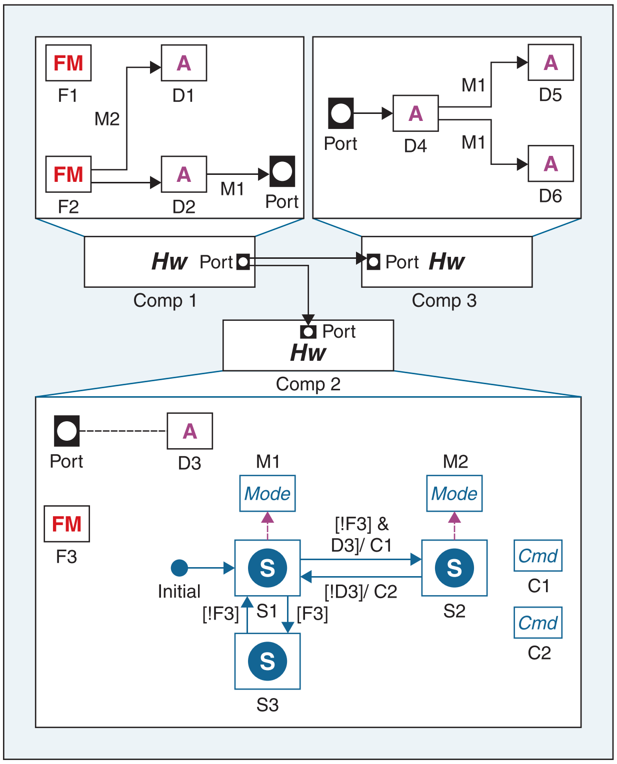

Fig. 3. Example TCD model. (Parts of this figure were created in a Graphical Domain Specific Modeling Environment/Tool for Temporal Causal Diagrams based on Generic Modeling Environment [24]).

This example illustrates the capability of the TCD model to capture:

- the fault propagations in the system,
- the behaviors of the protection elements in the nominal and faulty states, and
- the interaction between the fault propagation and behavioral models.

Power Transmission Systems

Relays and breakers protect power transmission system components, such as buses, lines, and transformers. The system includes backup relays to account for any problems in the primary relays and breakers. When a fault occurs, relays and breakers are designed to isolate the fault according to a pre-determined protection scheme.

Though a number of different protection elements exist, we only consider distance relays in this paper. The distance relays detect the presence of a fault by estimating the impedance using the voltage and current measurement at the relay measurement point. When a fault exists, the estimated impedance falls below the reach point impedance. Each distance relay is configured with specific impedance thresholds to detect faults in one or more zones (Zone1, Zone2 and Zone3). The distance relay compares the estimated impedance against the zone impedance thresholds to determine the fault zone.

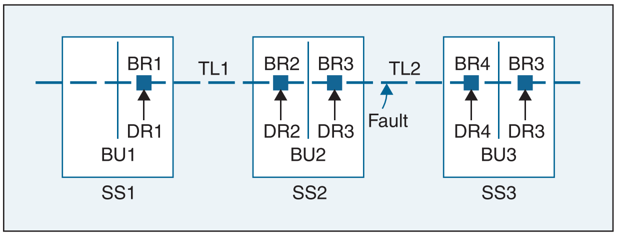

Fig. 4. A segment of a transmission line.

Consider the system shown in Fig. 4. It includes three substations (SS1, SS2, SS3) and two transmission lines (TL1, TL2). Transmission line TL1 carries power between buses BU1 and BU2, while transmission line TL2 is between buses BU2 and BU3. Though not shown on the diagram, we analyze the system assuming that power is being fed from both directions. Each transmission line has two breakers and two distance relay for protection.

Fig. 5 shows the relative location of fault zones (Z1: Zone1, Z2: Zone2, Z3: Zone3) and the corresponding representative regions of the transmission line (s1 , s2 , ..., s8) for each of the four distance relays (DR1, DR2, DR3, DR4). The exact boundary of each of these fault zones (and the intersecting regions) can be determined based on the topology of the power transmission system, the impedance per unit length of each transmission line, the length of each transmission line, and the settings of each distance relay such as its location, monitoring direction and zone impedance threshold settings.

A distance relay is typically configured to serve as both primary and as a backup protection device depending on the zone in which the fault occurs. For faults in Zone1 (Fig. 5), it serves as the primary protection and acts without any delay. For faults in other zones, the distance relay serves as a backup. It is configured to wait for a certain time (after fault detection) to allow the primary relay to respond to the fault. Typically, this value is around 5 to 6 cycles. (U.S. Grid frequency is 60Hz, i.e., 60 cycles per second.) The typical delay time for faults in Zone2 is 15-30 cycles, which is approximately 0.5 sec, and 1.5 s in Zone3. To account for transient faults in the transmission lines, relays include a fast and delayed auto-reclosure function wherein they check for the presence of the fault after around 2 s (fast reclosure) and after two to three minutes (delayed reclosure). If faults persist, the relay disconnects the circuit permanently until it is remotely commanded to reset. The fault zone impedance thresholds and the time delay parameters are configurable.

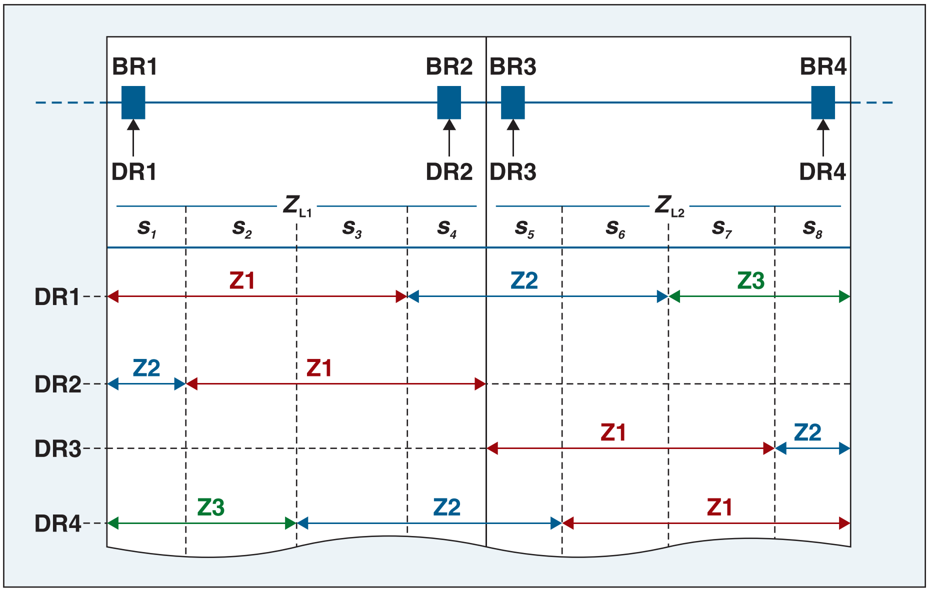

Fig. 5. Protection zone configurations for the distance relays shown in the figure above.

The Sequence Event Recorder (SER) at each substation collects data pertaining to the operations of the distance relay, the breaker status, other relevant events, and measurements. The remote terminal unit (RTU) in each subsystem sends the recorded data to the control center's Energy Management System (EMS). Some of the details recorded include:

- Zone information and protection action start time (in case of Zone1);
- Tripping command sent by relay to breaker;
- Breaker status, opened or closed;
- Phase discordance problem, when a breaker is not able to completely open all three phases;
- Reclosure command issued by the relay to reclose breaker; and
- Reclosure blocked command issued by relay to reset breaker to open after failed reclosure.

The TCD model of the system in Fig. 4 includes a fault propagation model to capture the effect of the faults in the transmission line, and the behavioral model of the breaker and distance relay components. The following subsections describe these models in detail.

Fault Propagation Model

Fig. 6 captures the propagation of the faults from the transmission lines to the discrepancies in distance relays. The failure modes (F_si) correspond to the segment si of the transmission lines (in Fig. 5) where the fault occurs. Discrepancies in the distance relays correspond to the three different fault-zones. Different line styles are used to distinguish the failure-effect propagation for different fault-zones.

Breaker Behavioral Model

The breaker behavioral model (Fig. 7) includes states Open, Close (initial state) and Part open. The breaker reacts to the open (C_Open) and close (C_Close) commands sent by the distance relay. Upon executing the command, the breaker changes state appropriately and reports the detected physical state of the breaker (ST_Open when open and ST_Close when close). The Open and Close states map to the system mode M_Open and M_Close, respectively.

The behavioral model deals with stuck open (F_st_open), stuck close (F_st_close) and partially open (F_part_open) faults in the breaker. The transition labels capture the nominal operation of the breaker to transition between open and close states in the absence of any of these faults. The presence of a stuck close (open) fault does not allow the breaker to transition out of the Close (Open) state.

Sometimes when commanded, a breaker cannot open all the phases (failure mode: F_part_open, state: Part_Open). When this fault is present, the breaker cannot transition or remain in the open state. While transitioning into Part_Open, the breaker reports its physical status to be the same as that in the Open state (ST_Open), but its mode maps to that in the Close state (M_Close). The circuit is not open (disconnected) because some phases are still not disengaged (closed).

Distance Relay Behavioral Model

The behavioral model of the distance relay (Fig. 7) captures the operation of the relay in response to detecting failure effects corresponding to faults in Zone1, Zone2 and Zone3. This is captured in terms of the discrepancies/ anomalies (d_z1, d_z2, d_z3) that are triggered (or are present) when the failures propagate from the transmission line to distance relay based on the fault propagation model captured in Fig. 6. Additionally, this model includes an internal fault, F_de, in the distance relay, which prevents it from detecting the discrepancies related to transmission line faults.

The model includes the following states:

- DET: state when the distance relay is actively looking for anomalies and triggering appropriate action upon detection,
- WAIT: when it is waiting for a time-out to expire before taking the next set of actions,
- BLK: when it is blocking and waiting for a reset command as it has taken the necessary action to arrest the fault propagation,
- DET_Error: when it is unable to detect anomalies because of internal fault (F_de),
- CHK_DET: The state where it checks if detection is feasible based on the current mode,
- NO_DET: The state when no detection is possible due to the current mode, and
- Reset: State corresponding to resetting of the distance relay.

The mode-information (M_Close, M_Open), the reset command (C_Reset) and the discrepancies for different fault-zones (d_z1, d_z2, d_z3) are input to the model. The outputs include the command to the breaker (C_Open, C_Close), the detection of Zone1 (Z1), Zone2 (Z2), Zone3 (Z3) discrepancies and the failure of fast-reclosure (FRBLK) and delayed re-closure (DRBLK).

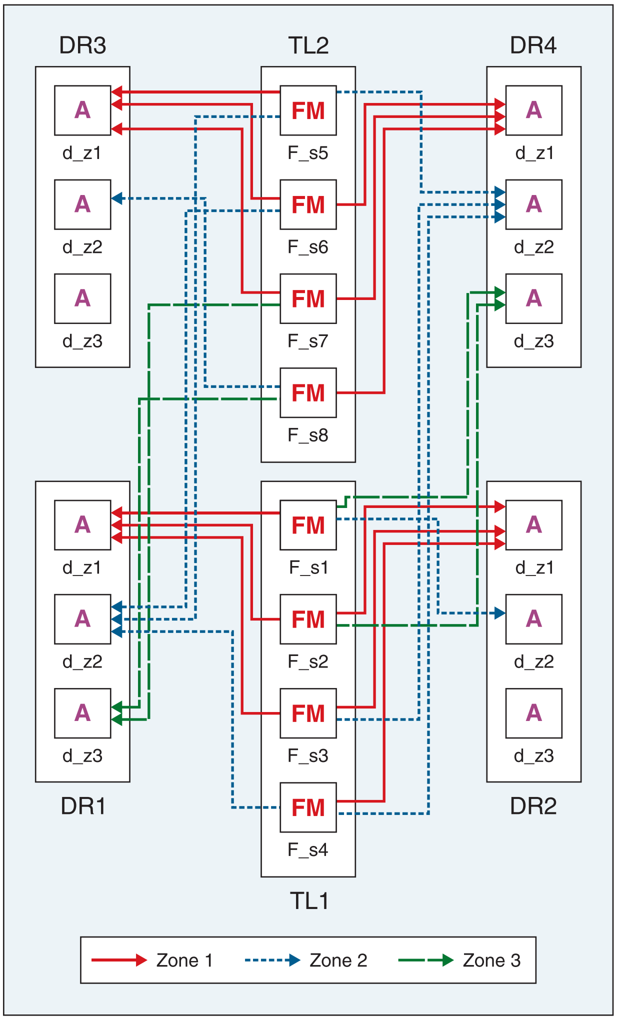

Fig. 6. Power transmission line fault propagation model. DR- distance relay. TL- transmission line. FM- failure mode.

The relay can move on to the detection state (DET) when the appropriate segment of the transmission line is closed (mode: M_Close) and there is no internal fault (F_de). When a Zone1 failure effect is detected (d_z1) for the first time (n=0), the distance relay immediately issues an open command (C_Open) and signals the presence of a Zone1 fault (Z1). It transitions to the WAIT state, with a wait-time (Tw=TFR) for checking fast-reclosure. Once the wait-time elapses, it transitions back to the CHK_DET state, while issuing a close command (C_Close) to the breaker. Upon breaker action, when the mode is closed (M_Close), the distance relay rechecks for the presence of Zone1 discrepancy. The relay resets itself if the discrepancy is found to be absent. Otherwise, it transitions back to the wait state, in the process issuing an open command (C_Open) and reporting a fast-reclosure failure (FRBLK) and setting the wait-time for delayed-reclosure. After the wait time elapses, the cycle is repeated to check for Zone1 fault. If present, the relay issues an open command (C_Open), reports a delayed reclosure failure (DRBLK) and transitions to the BLK state where it waits for a reset command to re-engage the breaker. The model uses an interval

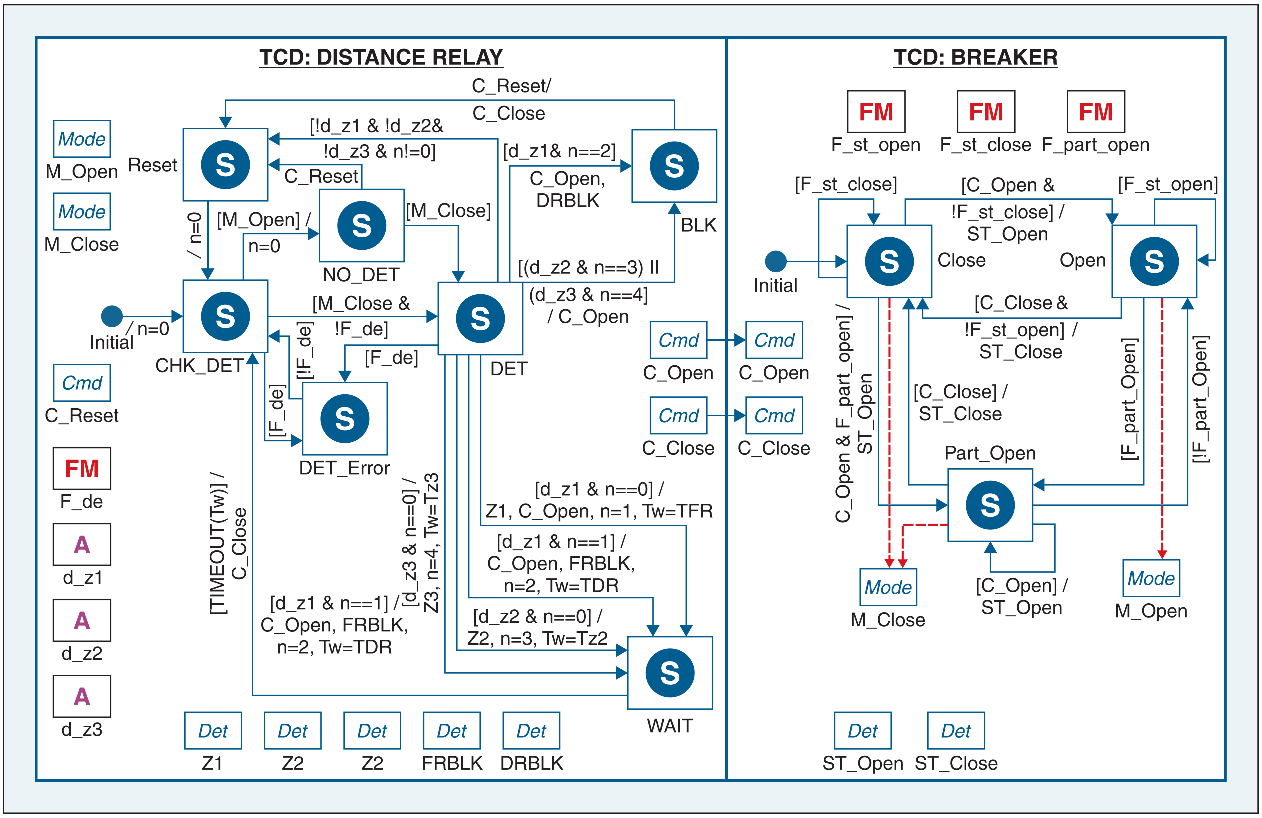

Fig. 7. TCD for distance relay and breaker. The model captures the interaction between the relay and breaker as well. Notice the command from the output port of the relay is connected to the input ports on the breaker behavior model. This figure was created in a Graphical Domain Specific Modeling Environment/Tool for Temporal Causal Diagrams based on Generic Modeling Environment [24].

variable (n) to keep track of its operation, while looping through these states.

In case Zone2 (d_z2) or Zone3 (d_z3) failure effects are detected, the system reports them (Z2, Z3) and transitions to the WAIT state. The wait time is configured to provide enough time for the primary relay to act. Once the wait time elapses, the system checks if detection is possible. If the primary had acted, no detection would be possible and the relay transitions to the NO_DET state. If the primary fails to act, and the discrepancy (d_z2 or d_z3) is detected again, it issues an open command (C_Open) and transitions to the BLK state.

When the fault F_de is present, the distance relay transitions to the DET_Error state. It gets out of this state only when the fault disappears. Thereby, when this fault is present, it does not transition to CHK_DET state to detect the anomalies.

Exclusive Set: The TCD behavioral model allows one to define Exclusive Set to group a set of events or variables wherein at most one event could be active at any point in time. When the set is defined over a set of Failure Modes (or Discrepancies), this implies that at most one Failure Mode (or discrepancy) can appear in the system at any given time. For example, in the case of the breaker, the Failure Modes F_st_open, F_st_close, and F_part_open are grouped into an Exclusive Set. This implies that in the breaker, at any given time, either none or at most one of these faults can be present. The set can be defined over other classes of events as well—Modes, Commands, Detection, etc. Examples of these cases include the breaker/ distance relay Modes (M_Open and M_Close), the breaker input commands (C_Open and C_Close), breaker status (ST_Open, ST_Close) and distance relay zone detection (Z1, Z2, Z3).

Parameters: Parameters can be defined and used in the TCD behavioral model. This allows certain values to be customized for the specific instance. In case of the distance relay TCD model, the parameters include the impedance thresholds for each of three zones and the wait times for relays when they serve as a backup protection elements (zone 2, zone 3) and the wait times for fast and delayed reclosure.

Discrete Event Simulation

The TCD model, like the one presented previously, allows one to capture the failure propagation and behavioral aspects of each of the components and create an integrated TCD model for the whole system (or subsystem). While such a model would serve as the basis for a TCD-based reasoning engine that attempts to explain the alarms and events observed in the system, it can also be translated into an executable discrete event simulation model that can generate the alarms, mode-changes and event traces for single and multi-fault scenarios. It can be used to simulate and study the behavior and evolution of the system in the presence of one or more faults in the

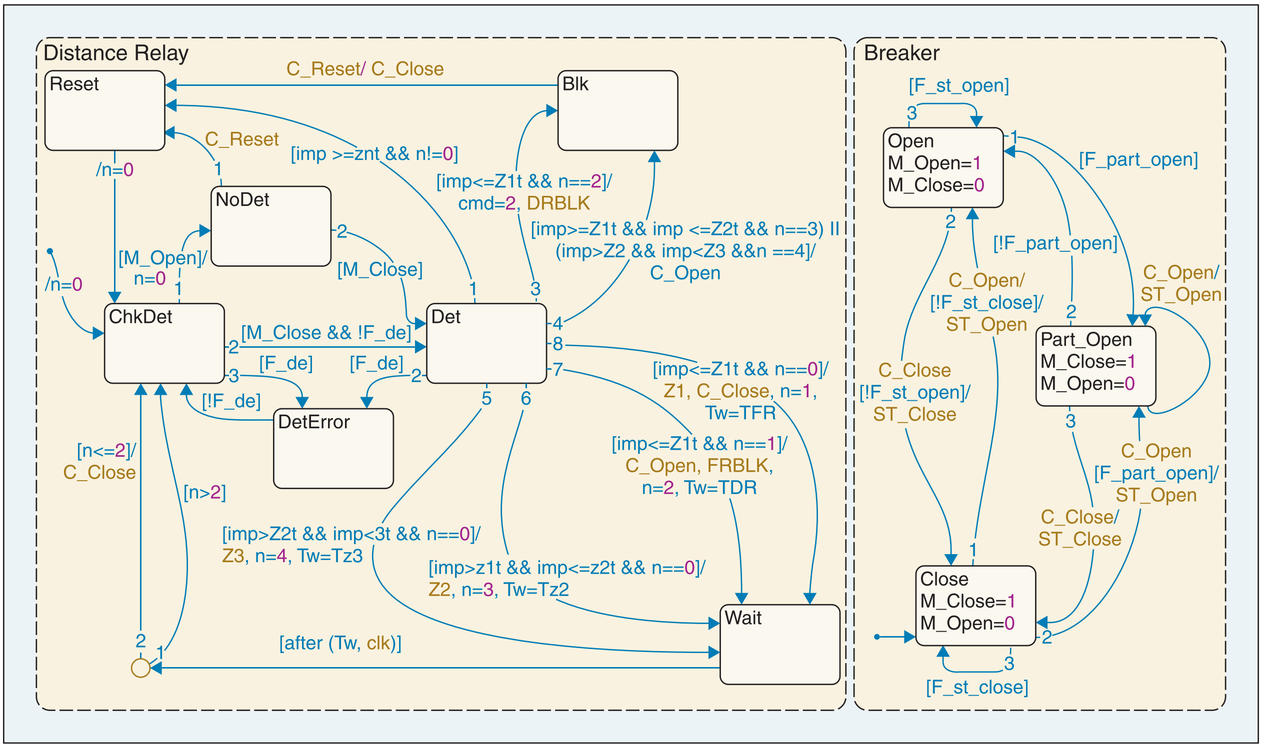

Fig. 8. Simulink stateflow model for distance relay and breaker.

protection and/or physical system. Such a study could also be useful to get a handle on the robustness and resilience of the system. More importantly, it can be used to generate data that can be used to test, validate and improve the quality and performance of the TCD based reasoner. Further, the richness of the collected data set can be improved by integrating the discrete event simulation model with other physical simulation models that can simulate the nominal and faulty operation of the physical plant.

Stateflow Models

In this section, we present the Simulink/ Stateflow discrete event simulation model that was created using the TCD models described earlier. (MATLAB, Simulink and Sateflow are registered trademarks of The MathWorks, Inc.) We present the event traces generated for a few fault scenarios.

The breaker and the distance relay TCD models in Fig. 7 were used to create the corresponding Stateflow models shown in Fig. 8. For the most part, the states, events and variables (faults, discrepancy, mode, command, status) in the Stateflow model are similar to those in the respective TCD model. A few changes have been introduced to capture the fault-propagation and fault-detection in the distance relay. The discrepancies related to Zone1, Zone2 and Zone3 failure effects are detected by comparing the observed impedance (imp) against the impedance thresholds for Zone1 (Z1t), Zone2 (Z2t) and Zone3 (Z3t).

Integrated Model: The integrated Simulink model shown in Fig. 9 captures the failure-propagation and behavioral aspects of the segment of power transmission system (Fig. 4). Each of the four breakers and distance relay units is represented by an instance of Stateflow model, shown in Fig. 8.

The configuration parameters and the topology of the power transmission system are set through a MATLAB script. The transmission line parameters include the length of each transmission line and its impedance per unit length. Each distance relay is configured with specific impedance thresholds for the fault zones (Zone1, Zone2, and Zone3) that it monitors. Further, adjacency matrices are used to define the topology in terms of the relative location of the transmission line and distance relays. Any updates to this set up, in terms of faults (in the transmission line, breaker and distance relay) and their triggering times are input through MATLAB scripts.

A MATLAB function computes the observed impedance for each distance relay based on the topology and configuration parameters. During the simulation, each instance of the State-flow model is updated with the observed impedance and fault status corresponding to the distance relays and breaker that it represents.

Simulation Results

System Configuration

The integrated Simulink model described above is used to simulate single and multi-fault-scenarios for the example power transmission segment described earlier. Let us assume that the lines have an impedance of 100 ohm across the whole length (uniform impedance per unit length). Both DR1 and DR4 are set with a Zone1 impedance threshold of 80 ohm, Zone2 threshold of 150 ohm and Zone3 threshold of 195 ohm. DR2, DR3 are set to monitor only in Zone1 and Zone2 regions—with

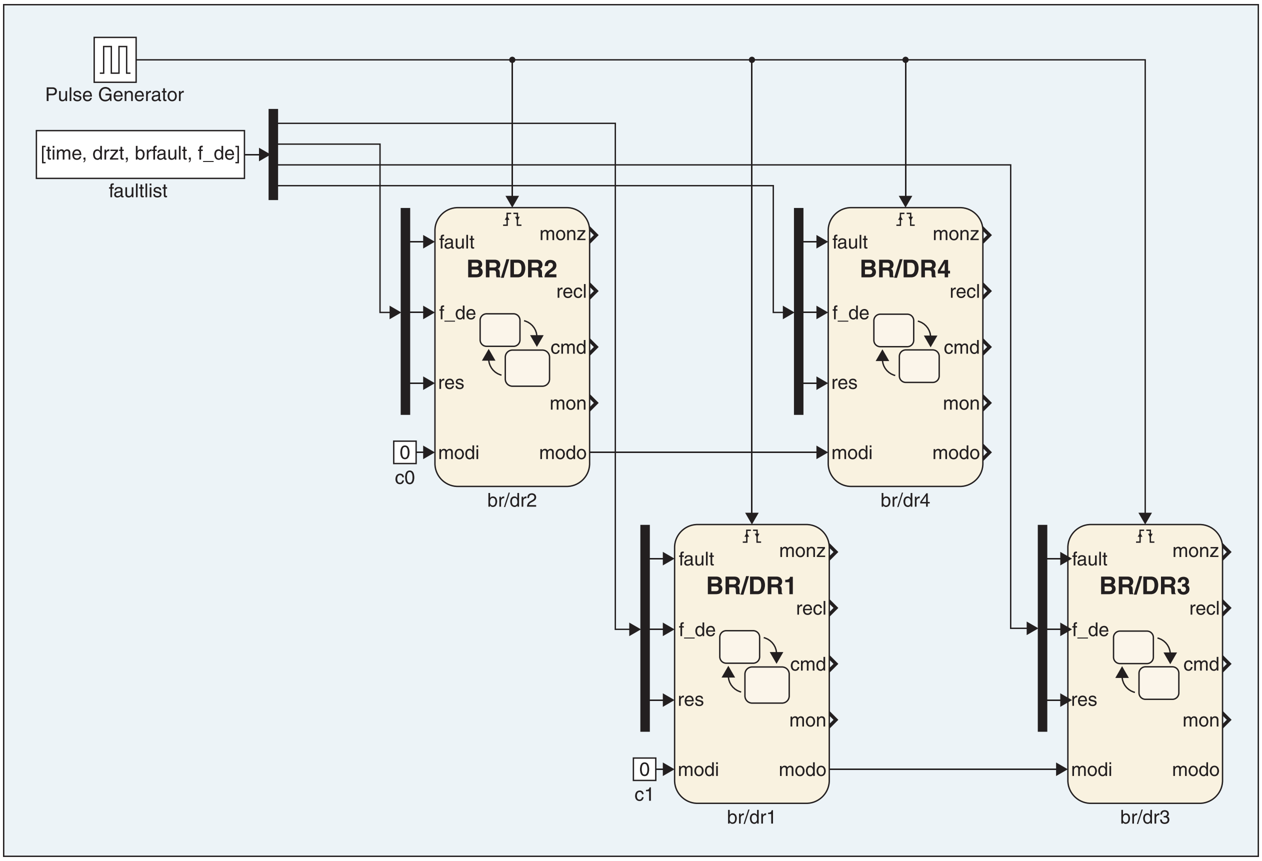

Fig. 9. Complete Simulink model of the system shown in Fig. 4.

impedance threshold of 80 ohm for Zone1 and 95 ohm for Zone2. They are not configured for Zone 3. The autoreclosure wait times in the distance relays are set to 2 s (fast reclosure) and 100 s (delayed reclosure). The wait times for the backup relays are set to 0.5 s (Zone2) and 1 s (Zone 3).

Simulation Result

The scenarios and events generated from the simulation are discussed below.

Temporary Transmission Line Fault: In this scenario, a line to ground fault was introduced in the transmission line (TL1) at 40% of its total length (measured from distance relay DR1) at time=10 s. Being a temporary fault, it disappeared at time = 11 s.

Fig. 10 shows the impedance observed by the distance relays around the time of the fault. The initial impedance around 9.5 s corresponds to the nominal impedance observed by relays, which can be verified by computing the impedance based on the topology, transmission line impedance and relay location. At around 10 s, the observed impedance in relay DR1 drops to 40 ohms, which is consistent with the fault- location (40% of the length of TL1). DR2 drops to 60 ohms and DR4 to 160 ohms. DR3 is unaffected because it is not observing along this direction. The gap in the impedance plots occurs when the circuit is disconnected by opening one or more breakers. When the breakers are closed and the fault disappears, the impedances are restored to their nominal values.

Fig. 11 shows the zone report from each of the distance relay in response to the change in observed impedance. DR1 and DR2 report a Zone1 fault, while DR4 reports a Zone3 fault, which is consistent with the zone impedance thresholds. The effect of the commands issued by the distance relay (in response to the fault detection) can be seen in Fig. 12, which shows the physical state reported by the breaker. It can be seen that the breakers BR1 and BR2 were opened a little after time=10 s, in response to the commands issued by the distance relay. There is no need for the backup relay DR4 to act, as the primary relay DR2 has acted correctly. Hence, there is no change in state of breaker BR4.

The breakers BR1, BR2 are closed at time=12 s, as relays DR1, DR2 perform the fast auto-reclosure (after a 2 s wait). Since the fault disappears at time=11 s, the observed impedances (Fig. 10) are restored to their nominal values. Hence, no further action is taken and the breakers are left in the closed state.

Transmission Line and Distance Relay Fault: This scenario deals with a faulty relay DR2 (Failure Mode: F_de), which cannot detect discrepancies related to impedance changes. Also, a persistent line to ground fault appears in the transmission line (TL1) at 40% of its total length (measured from distance relay DR1) at time=10 s.

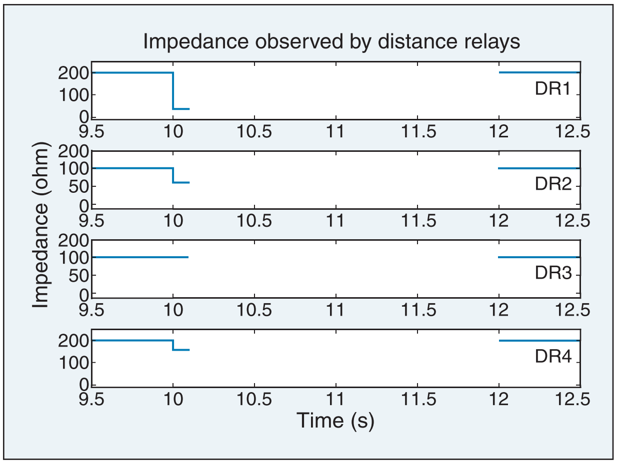

Fig. 10. Scenario 1: Impedance observed by distance relays.

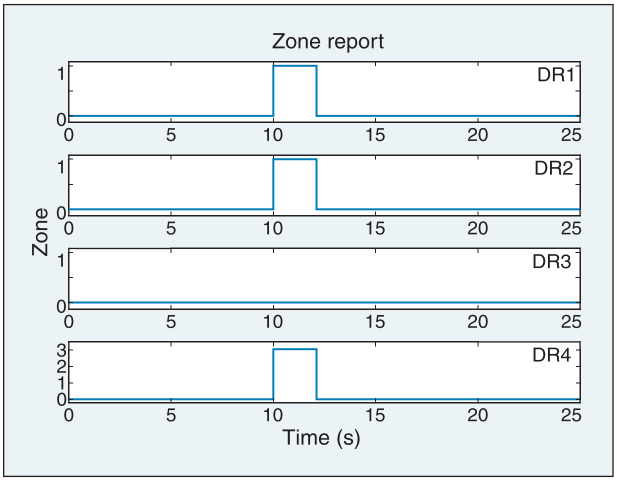

Fig. 11. Scenario 1: Zone report.

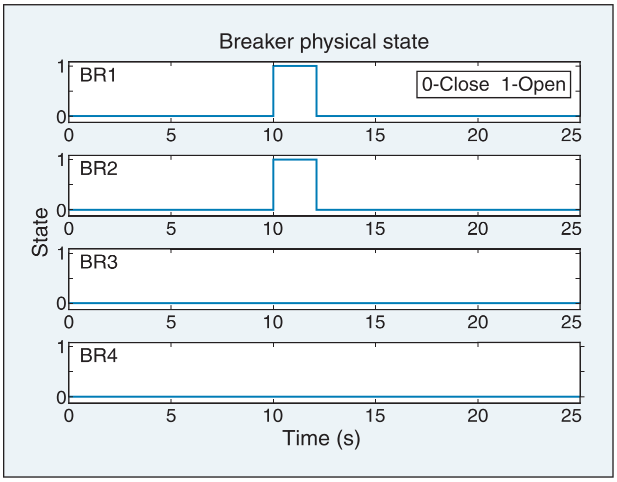

Fig. 12. Scenario 1: Breaker physical state.

Fig. 13 shows the zone report from the distance relays. DR1 reports a fault in Zone1, DR4 reports a fault in Zone3 and DR3 does not see any change as the fault is outside its configured zone/ direction. Even though the fault occurs in the zone 1 of DR2, it does not detect any zone fault due to the presence of the detection fault (F_de). As a result, there is no change in the

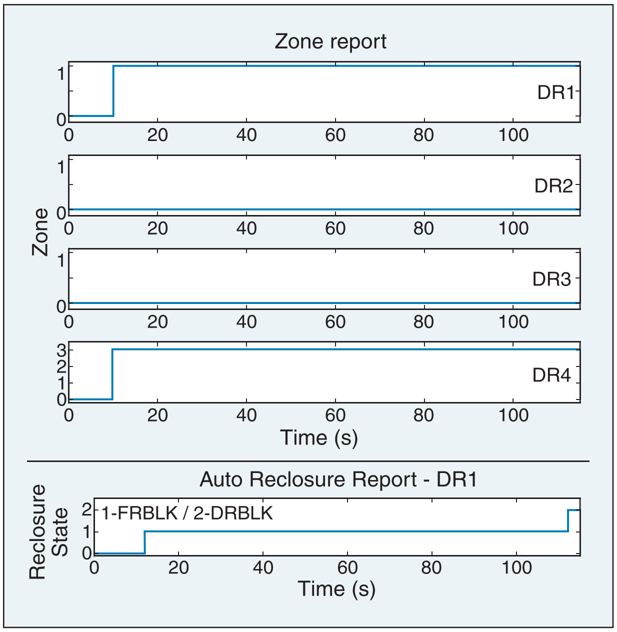

Fig. 13. Scenario 2: Zone & auto-reclosure report.

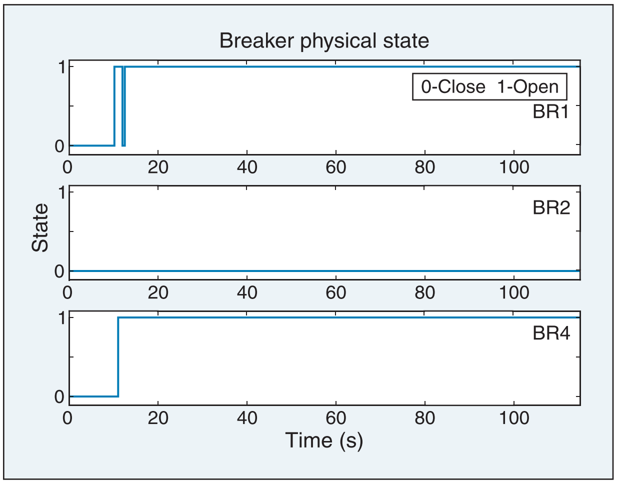

Fig. 14. Scenario 2: Breaker physical state.

status of the breaker BR2 (Fig. 14). With the failure of the primary relay (DR2), the backup relay (DR4) acts by opening the breaker BR4 (Fig. 14).

The effects of the auto reclosure behavior in primary relay DR1 can be seen in the last plot of Fig. 13. The breaker BR1 is closed for a very short period around time=12 (fast reclosure or FRBLK) and time=110 (delayed reclosure or DRBLK). Since the transmission line fault is persistent, the relay DR1 detects a fault in Zone1 after each reclosure and opens the breaker (BR1).

Conclusion

We introduced the modeling paradigm of Temporal Causal Diagrams (TCD) in this paper. TCDs capture fault propagation and behavior (nominal and faulty) of system components. An example model for the power transmission systems was also described. This TCD model was then used to develop an executable simulation model in Simulink/Stateflow. Though this translation of TCD to an executable model is currently done manually, we are developing model templates and tools to automate this process. Simulations results (i.e., event traces) for a couple of single and multi-fault scenarios were also presented. As part of our future work, we wish to test and study the scalability of this approach towards a larger power transmission system taking into account a far richer set of protection elements. Further, we wish to consider more realistic event traces from the fault scenarios including missing, inconsistent and out-of-sequence alarms and events.

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Nagabhushan Mahadevan (nag.mahadevan@vanderbilt.edu) is a Senior Research Engineer at the Institute for Software Integrated Systems, Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN. His work involves research in model-based diagnostics, verification and validation of health management systems, and resilience in cyber-physical systems. He received his M.S. degree in Computer Engineering and Chemical Engineering from the University of South Carolina, Columbia, and B.E. degree in Chemical Engineering from Birla Institute of Technology and Science, Pilani, India.

Abhishek Dubey is a Research Scientist at the Institute for Software Integrated Systems, Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN. His research interests are related to resilient cyber-physical systems and fault diagnosis in distributed software systems. He received his Ph.D. in Electrical Engineering from Vanderbilt University in 2009 and B. Tech. in Electrical Engineering from Indian Institute of Technology, BHU, Varanasi, India in 2001.

Gabor Karsai is a Professor of Electrical Engineering and Computer Science at Vanderbilt University, and Senior Research Scientist at the Institute for Software-Integrated Systems. He conducts research in the design and implementation of cyber-physical systems, in programming tools for model-driven development environments, in the theory and practice of model-integrated computing, and in real-time fault diagnostics. He received his B.Sc., M.Sc., and Dr. Techn. degrees from the Technical University of Budapest, Hungary, in 1982, 1984 and 1988, respectively, and his Ph.D. from Vanderbilt University in 1988. Dr. Karsai has worked several large DARPA projects in the recent past: advanced scheduling and resource management algorithms, fault-adaptive control technology that has been transitioned into aerospace programs, and model-based integration of embedded systems whose resulting tools are being used in embedded software development tool chains.

Ajay Chhokra is a Ph.D. student in the Department of Electrical Engineering, Vanderbilt University, Nashville, TN. He received his Bachelor's degree in Electronics and Communication Engineering from Punjab Technical University in 2010. His research interests include model-based design of embedded systems, model integrated computing, system diagnosis and verification.

Huangcheng Guo is a Ph.D. student in the Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN.