Test Bed for Cascading Failure Scenarios Evaluation

Ahmad Abdullah, Ahad Esmaeilian, Gurunath Gurrala, Papiya Dutta, Tomo Popovic, Mladen Kezunovic

***Abstract*-- This paper presents a simulation test bed aimed at evaluation of relay operation under faults leading to cascading events. The test bed uses physical relays and waveforms replayed from the Alternative Transients Program (ATP) simulations. A system level tool which identifies probable cascade scenarios for the given load condition and topology is presented. These scenarios are analyzed for zone-3 misoperation on any of the overloaded lines which may lead to cascading events. The fault scenarios are simulated in ATP and the generated wave forms are used to test operation of actual relays. The relay operation evaluation has been performed using SEL 421 distance relay utilizing an open-loop transient testing simulator. The IEEE 118 bus system is used for creating test cases.**

***Keywords*: cascading scenarios, power system relaying, protective relaying, cascading outages, cascading failure, power system analysis, blackout.**

I. INTRODUCTION

ELECTRIC power system is one of the largest and most complex man-made systems. It is exposed to all kinds of threats since it typically covers large geographic area. Too many factors, such as weather, human errors, natural disasters, tree/animal contacts, equipment malfunction, etc., can result in disturbances, i.e., faults and unplanned outages, in the power system. This paper is focused on a more severe kind of system disturbances: cascading outages, which refers to the uncontrolled successive loss of system elements triggered by a disturbance [1]. Historical evidence suggests that large area blackouts are always the final results of cascading outages [1]. There are lots of factors making power system vulnerable to cascading outages, which can be classified into two groups [2]: a) non-technical factors, such as change in operating procedures due to deregulation, aging infrastructure and lack of investment, and inadequate personnel training for dealing with new operating conditions, b) technical factors, such as operating difficulties, increased system complexity, more difficult protection setting coordination, inadequate traditional security analysis, lack of understanding of the cascades and unavailability of effective support tools [3].

This paper deals exclusively with the second group of factors and more specifically with distance relay misoperation. Zone-3 operation of distance relays during an un-faulted condition is a very common occurrence in many of the historical blackouts. Relays may observe a low voltage and a high current during an overload, power swing, or low voltage event and as a consequence trip an otherwise healthy component. This action leads to further power flow changes, overloads, and voltage problems for a weakened system. Identification of a relay misoperation using simple and accurate fault detection and classification scheme and returning the line to service may prevent occurrences of large-scale cascading blackouts.

There have been several attempts in the literature to create cascading event scenarios based on system level vulnerability studies using steady state analysis tools [4]. The main purpose of cascading failure detection and vulnerability study is to identify conditions in the power system that may lead to a sequence of cascading outage events of system components. Such a sequence can eventually result in system blackout [5].

The paper focuses on use of the IEEE 118-bus system with a goal to simulate several fault and cascading failure scenarios that will provide credible test data to apply to a physical relay. IEEE 118 model has been created in ATP [6] for fault scenarios simulation. The cascade scenarios are created using steady state analysis tools in MATPOWER and Octave [7], [8]. Experimental test set-up using Relay Assistant software and an open-loop low-voltage simulator have been used in the lab setup [9]. Fault and cascading scenarios have been tested in the lab using a Schweitzer SEL-421distance relay [10]. The rest of the paper is organized as follows. The concept of automatic creation of fault scenarios in ATP is introduced in Section II. The system level tool for probable cascade scenario detection is explained in section III. The experimental test bed and results are described in section IV. Section V summarizes the conclusions.

II. FAULT SCENARIOS

Creating large number of fault scenarios in ATP for research purposes is often necessary. Implementing an

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A. Abdullah is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail of corresponding author: ahmad.abdullah@ieee.org).

A. Esmaeilian is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: ahadesmaeilian@neo.tamu.edu).

G. Gurrala is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: ggurrala@ece.tamu.edu).

P. Dutta is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: papiya82@neo.tamu.edu).

T. Popovic is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: tomo@ece.tamu.edu).

M. Kezunovic is with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: kezunov@ece.tamu.edu).

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effective script for creating a large number of fault scenarios simulations is discussed here. The script has been implemented using GNU Octave [8]. The transmission line length, line impedances, fault type, location of fault, fault resistance as well as fault inception angle are inputs to the software. Fig 1 shows the steps involved in this process. To create different scenarios there are four variables which can be specified independently. They are fault type, fault location, fault resistance and fault inception angle. The fault generation script automatically changes these variables and creates different scenarios. The main ATP file is created for the system using ATPDraw [11]. The transmission lines are split into two sections instead of having a single section. Both lumped and distributed transmission line models can be used for these scenarios. The mid-point of the two sections needs to be numbered so as to identify the line easily for coding purposes. A switch as shown in Fig. 2 is added in the ATPDraw without connecting to any component. Its node is denoted with a unique name for easy identification. The generated ATP file from ATPDraw is used as a reference file for fault scenarios simulation.

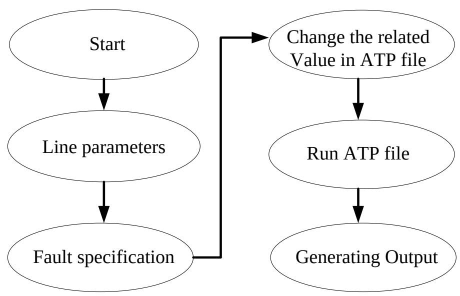

Fig 1. Fault generation script structure

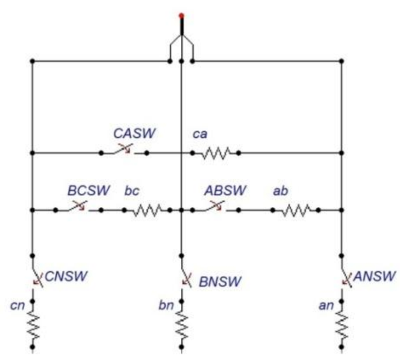

Fig. 2. Switch configuration for fault simulations

A new file will is created from the reference file each time a new fault scenario is simulated. The main logic in the program is to search for from-node number and its mid-point number in the new ATP file corresponding to the first half section of the transmission line that is being faulted. The corresponding *R* and *X* values are changed to the *pR*/100 and *pX*/100 where *p* is the percentage fault location. Similarly search for the other half-section of the transmission line in the ATP file is performed by changing the *R* and *X* values accordingly. Now the switch node number is changed to the mid-point node number of the line to be faulted. Then the switch status, timings and fault impedances are changed as per the desired scenario. The resulting ATP file will be simulated to obtain the waveforms. This process can be iterated for large number of fault scenarios.

The transmission lines considered for different fault scenarios creation in IEEE 118 bus test system are shown in Table 1.

The following fault conditions are generated:

1. Distance to fault from one end of a line is changed to be 5%, 20%, 30%, 40% and 50% of the length of the line.
2. Fault resistance at the fault point is changed to be 0Ω, 10Ω, 20Ω, 50Ω and 100Ω.
3. Four types of faults are considered (a-g, ab, ab-g, abc).
4. As a result ,the total number of cases for each system is: 500 (5 lines x 4 faults x 5 fault resistance x 5 fault distance).
5. Few fault cases have been created varying fault inception angles (0^0, 40^0, 80^0, 120^0 and 160^0 are considered).

TABLE I
LINES CONSIDERED FOR FAULT SCENARIOS – IEEE 118 BUS SYSTEM

Case #	From Bus	To Bus	Length (miles)	Voltage (kV)
1	30	38	165	345
2	54	49	124	138
3	16	12	36	138
4	82	83	17	138
5	8	30	154	345

III. CASCADING SCENARIOS

The cascading scenarios created in this paper are solely based on overloads. This means that when a line is tripped following a fault it can cause overload on another line, and when this second line is tripped because of fault, that causes an overload on another line and so forth. The assumption here is that few events will happen before zone-3 of the relay miss-operate on overloads. The events can be loss of lines, sudden increase in load or generation etc. Emergency rating of the line is considered as the loading limit of the lines. The lines which have highest overload following a trip are considered as the next candidate lines for tripping. After that, each overloaded line is a case by itself. Tripping these lines and observing if each line trip causes more overload on other lines answers the question of cascade. The flowchart of the script for automatic generation of scenarios is shown in Fig. 3. This script was also created in Octave. These scenarios may not always result in zone-3 tripping; some more selective line trips surrounding the overloaded lines might be needed for zone-3 settings to operate. Three successful scenarios have been generated on IEEE 118 bus system. It should be noted that the data used in simulating the IEEE 118 case is taken from [12]. The power flow engine that was used in obtaining the steady state currents is a modified version from MATPOWER [7]. In the following scenarios all relay settings are obtained using the algorithm given in [13]. The current approach differs from [14] where probability and reliability are included in predicting the cascading path based on a certain load pattern. This paper does not consider the reliability and probability in creating the scenario.

A. Scenario-1

This scenario assumes two line outages due to fault, and this cause a relay misoperation.

1. Outage of line #7 (line 8-9) due to fault.
2. Another fault that occurs on line #104 (line 65-66) causes that line to be taken out of service.
3. The outage of these two lines causes the relay at bus 69 of line #108 (line 69-70) to misoperate. The third zone relay setting at node 69 is 126 Ω. The voltage at node 69 is 1.035 pu and the apparent impedance is (64.46+j31.98) Ω.

This combination causes a trip in the third zone. The scenario is depicted in Fig. 4. It should be pointed out that there are other variations of this scenario. For example, instead of line#7 outage, the generator at bus-10 outage results in the same misoperation.

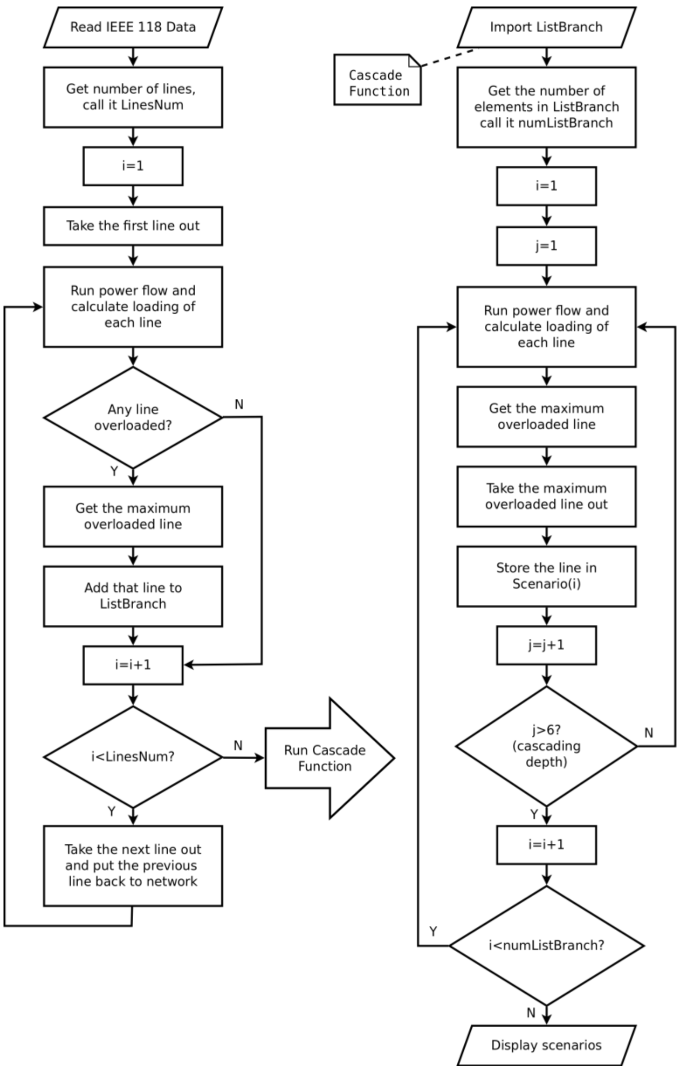

Fig. 3. Flowchart for creation of cascade scenarios

B. Scenario-2

This scenario assumes faults on four lines in any order as follows.

1. A fault on line #164 (line 100-104) causes the line to be tripped and the loading on the line #167 (line 100-106) increases by 28%.
2. If subsequent fault occurs on line #167, this causes the line to be tripped and the loading increases on #174 (103-110) by 25%.
3. Another fault on line #168 (line 104-105) takes that line out of service as well and the loading increases on line #174 (line 103-110) by an additional 25 %.

If another fault hits line #174 and takes that line out of service then the relay at bus 103 of line 103-105 will misoperate and trip in the third zone. The third zone relay setting at node 103 is 93 Ω. The apparent impedance at bus 103 is (60.28+j25.6) Ω and the voltage is 1.01 pu. Scenario-2 is shown in Fig 5.

C. Scenario-3

This case assumes outage of several lines and a generator.

1. The generator at bus 65 is taken out for maintenance or due to an internal fault.
2. The outage of line #116 (line from 69 to 75) due to a fault, causes the loading on line #108 (line from 69 to 70) to increase by 43 %.
3. Tripping of line #126 (from 68 to 81) due to fault causes the loading on line #108 to increase by 12 %.
4. If another fault occurs at line #104 (from 65 to 68) and causes tripping of that line then the relay at bus 69 of line #108 (line 69-70) miss operates and trips in the third zone.

In fact it turns out that the relay at node 69 will misoperate for much more events than mentioned in this paper and special attention must be paid to this relay. The setting of zone 3 of that relay is 126 Ω and the apparent impedance which was flowing in the line just before the relay misoperates is (72.86+j24.28) $^{\Omega}$.

IV. Experimental Test Bed and Results

Relay Assistant is an open-loop transient testing tool for protective relays. It is capable of sending signals from file formats such as ATP PL4 [6], and COMTRADE [15] to any relay connected to the I/O box which does the necessary analog to digital conversion. The block diagram of the setup is shown in Fig. 6. In the present set up only one relay is used. Signals from two ends of the line with corresponding settings on the relay are independently applied to SEL 421 relay. Event files in COMTRADE format are collected from the SEL 421 relay.

Few representative experimental results are shown in the following paragraphs. They are divided into two parts, one about the fault cases simulation while the other about cascading scenarios verification.

A. Fault Cases

Fig. 7 shows voltage and current waveforms obtained from the event files of the SEL-421 for a fault scenario. These waveforms are retrieved from the SEL421 relay using acSELcelerator [16] which is a software build by SEL labs as an interface to the SEL relay. This case corresponds to a 7 cycle’s 3-ph fault at midpoint of the line 82-83 created using the procedure explained in section II.

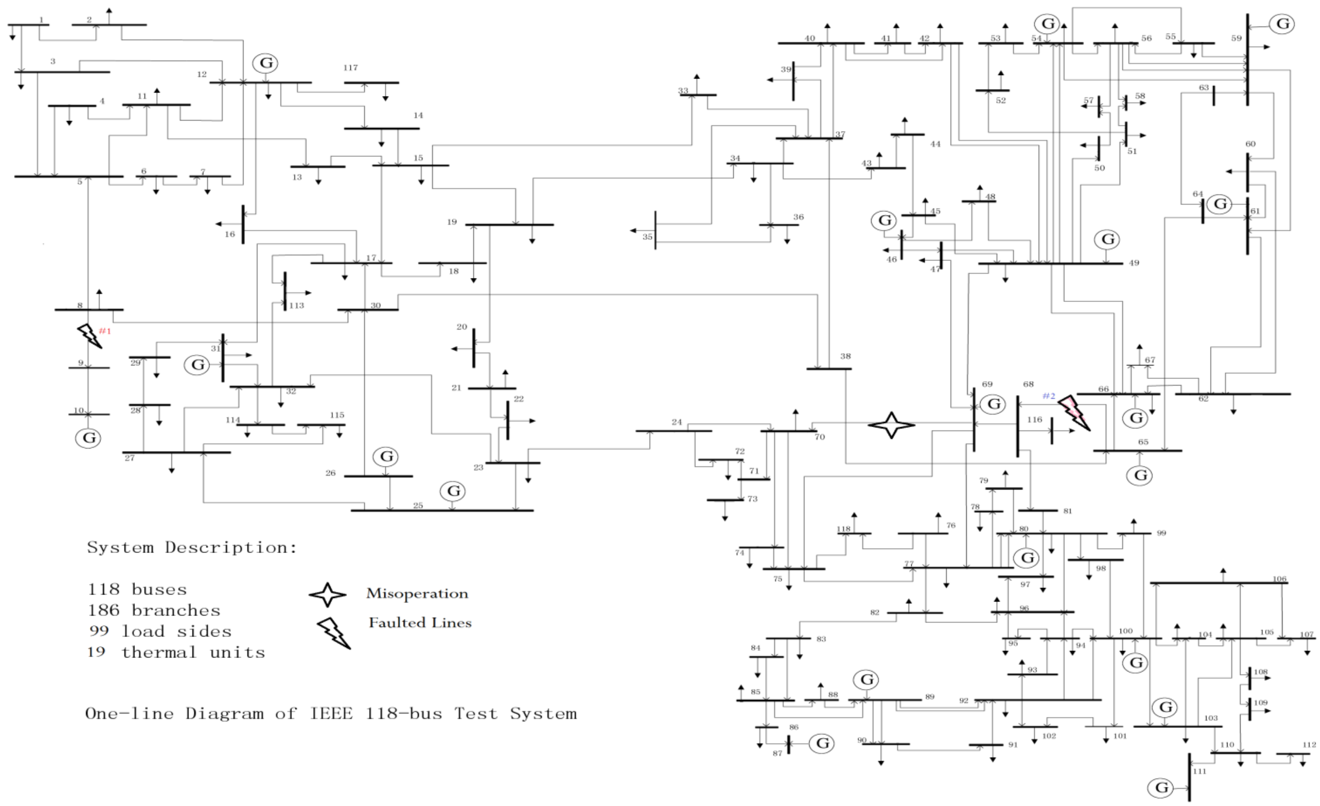

Fig. 4. Scenario-1: The relay at bus 69 of line 69-70 trips in the third zone

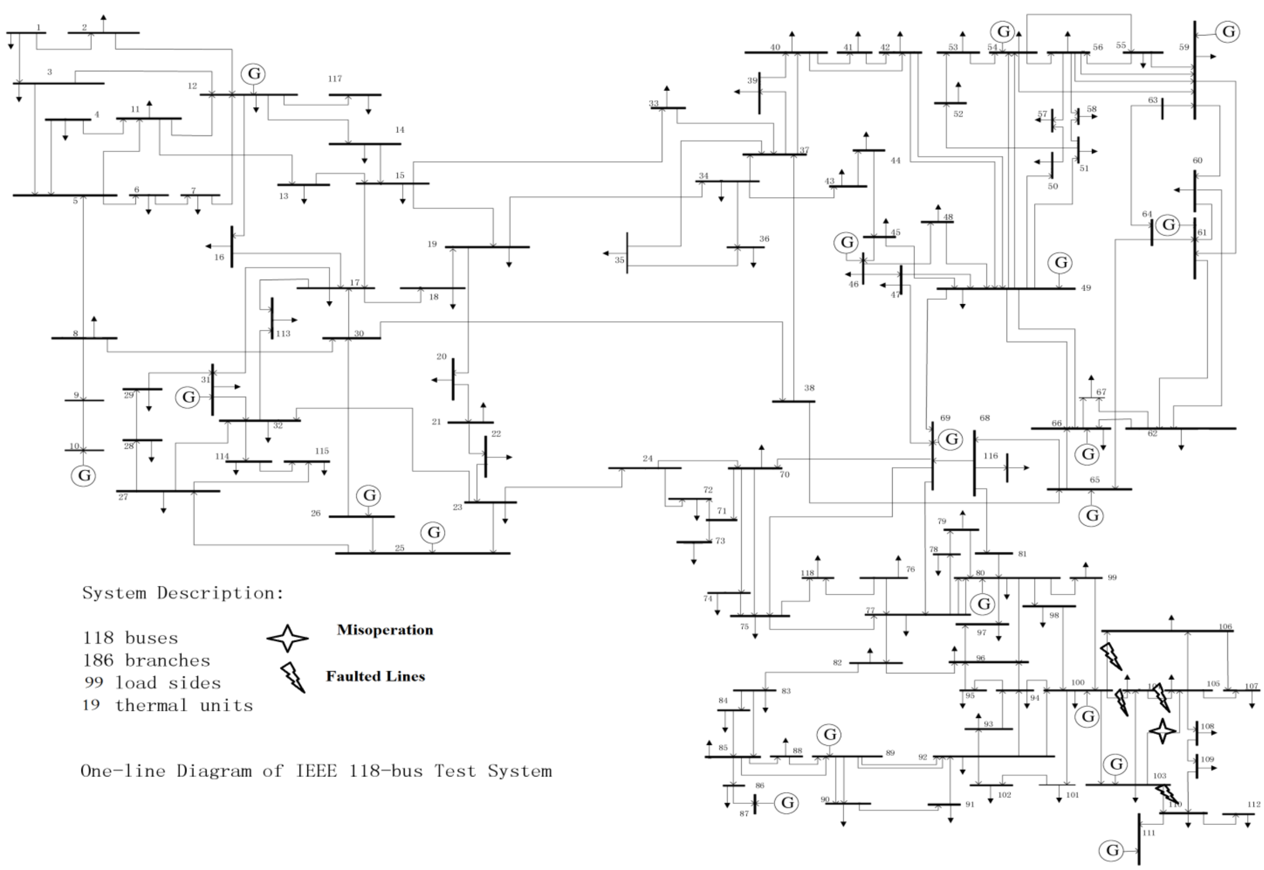

Fig. 5. Scenario-2: The relay at bus 103 of line 103-105 trips in the third zone

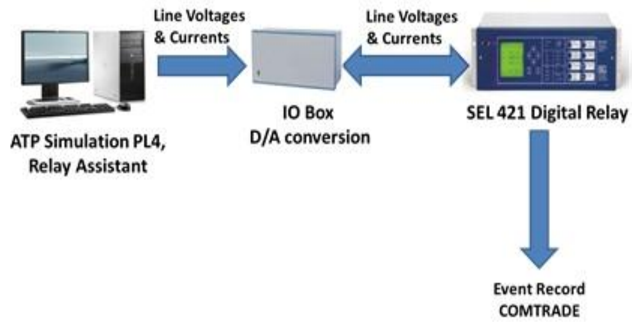

Fig. 6. Schematic of cascade scenario experimental test bench

Waveforms from ATP simulations are saved at 2 kHz sampling rate for this fault scenario. These signals are played back on SEL-421 using relay assistant. SEL-421 is loaded with settings corresponding to relay at node-82. It can be observed from the figure that the relay is tripped and issues a trip signal (marked by red vertical dotted line).

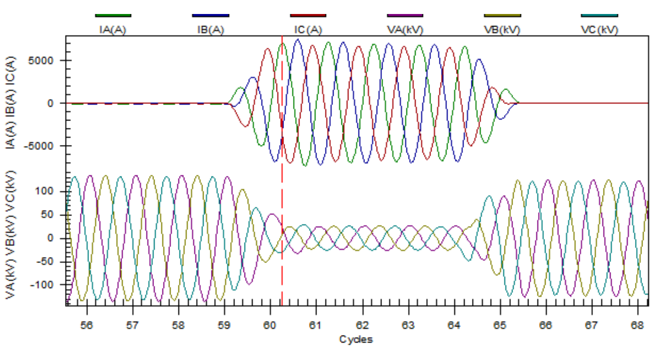

Fig. 7. Fault case on Line 82 -83, Node 82

B. Cascading Scenarios

Relay Assistant has a waveform generation capability. The steady state voltage and current values calculated from the load flow before and after the last event in each cascade scenario are used to create the corresponding waveforms in Relay Assistant.

Scenario-1. Fig. 8 shows the SEL421 event record voltage and current waveforms seen by relay at bus 69 on transmission line 69-70 after the last event in Scenario-1, which is tripping of transmission line 65-66. The trip signal is shown by a vertical dotted line.

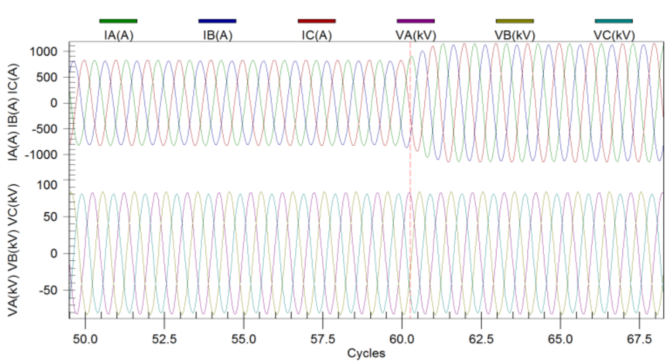

Fig. 8. Scenario-1: current and voltage waveforms retrieved from the relay

Scenario-2 is verified using waveforms from ATP simulations. As the ATP model is created with constant voltage sources for fault scenarios, cascade scenarios simulation results in incorrect steady state results if the voltage sources are set to the base case magnitudes and angles. For relay misoperation the steady state values after the last event are important. So for Scenario-2, the steady voltage magnitudes and angles after the last event, outage of #174 (line 103-110), are used for all the constant voltage sources. Simulation is run with the post event conditions by taking out the lines #164 (line 100-104), #167 (line 100-106). Now the lines corresponding to last event i.e. Line #174 (line 103-110) and #168 (line 104-105) are then switched at 0.7s. The results of this ATP simulation are shown in Fig. 9. It should be noted that the waveforms prior to the last event are not exact representation of the expected steady state values; however the post event steady state values represent the exact steady which is important for relay misoperation. The plot file (PL4) of the ATP simulation is stored at 2 kHz sampling rate. Relay Assistant is used to import the PL4 file and corresponding voltage & current waveforms are played on SEL-421 with the settings of relay 103. Fig. 10 shows the waveforms obtained from SEL421. It can be observed that the relay trips during the post event period confirming the validity of the scenario.

Scenario-3. Fig. 11 shows the voltage and current waveforms seen by relay at bus 69 on transmission line 69-70 after the last event in Scenario-3, which in this case is tripping of transmission line 65-68. This case also resulted in zone-3 tripping. The trip signal is shown by a vertical dotted line. Usually, zone-3 time delay will be set to 60 to 75 cycles. As the relay captures only few cycles of data, the delay is set to zero to capture pre-event and post event waveforms.

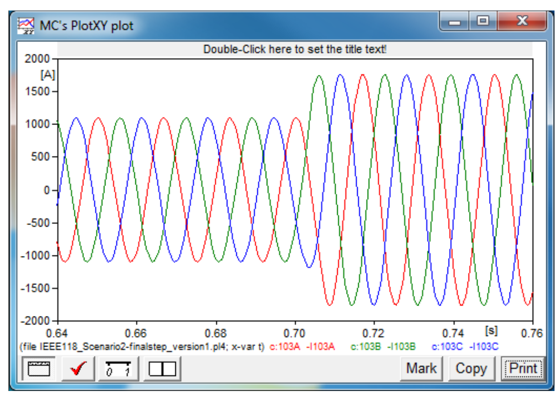

Fig. 9. Scenario-2: current waveforms from the ATP simulation

This experimental set up is still evolving. As of now only single relay is used for checking zone-3 tripping. This approach only confirms zone-3 tripping but does not give any indication of whether this happens due to cascade or due to a fault in zone-3 region. Test set up expansion to accommodate two relays for simultaneous replaying of signals corresponding to one primary and backup relay pair is under progress. The event can be recognized as a cascade if the backup relay trips in zone-3 but there is no fault detected in the primary relay in any of the other zones. Future work is targeted to simulate cascade scenarios in ATP including detailed models of synchronous machines.

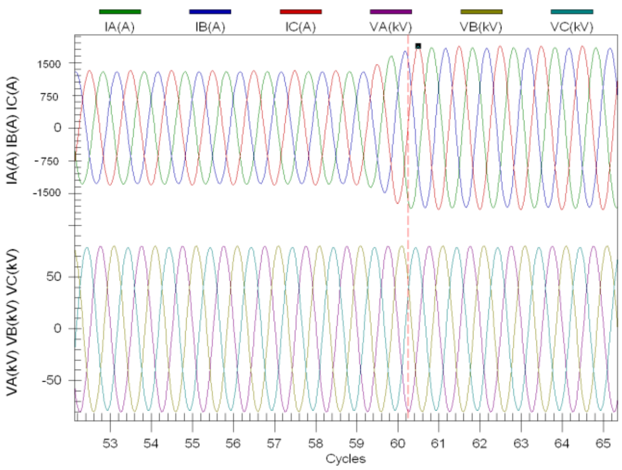

Fig. 10. Scenario-2: current and voltage waveforms retrieved from the relay after the PL4 waveform playback

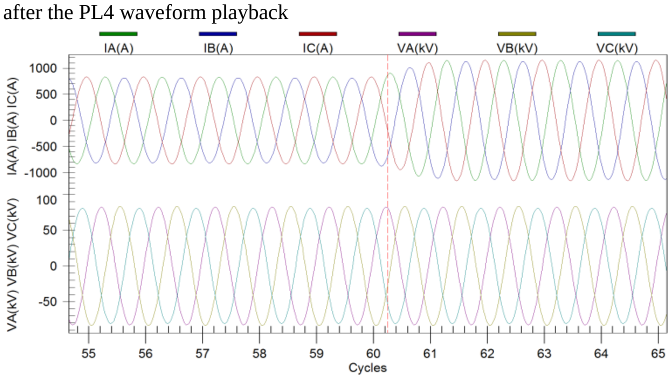

Fig. 11. Scenario-3: current and voltage waveforms retrieved from the relay

V. Conclusions

The Focus of this paper has been on distance relay zone-3 misoperation since this is a common cause of cascading events. In this paper the IEEE 118 model has been used to generate cascading events but any model can be used as well. The following are paper contributions:

- A programming approach to create automatic fault scenarios using ATP and MATPOWER has been implemented.
- A method of creating probable cascade scenarios has been utilized to create cascade scenarios which result in zone-3 tripping of the overloaded lines. Simulations have been done for the IEEE 118 bus test system.
- An experimental set up consisting o f a transient simulator connected to SEL 421 distance was utilized to verify relay misoperation.

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