Simulation Board for Smart Service Restoration Schemes in Distribution Grid

ZACHARY CHEBEN, JESSICA ILAGAN, JOSHUA MILLER, LONG-GIANG NGUYEN, KEVIN STEIDEL, JOSE VENTURA, SUTHASINEE VIRNIG, HA THU LE

Department of Electrical and Computer Engineering
California State Polytechnic University, Pomona
Pomona city, California 91768
UNITED STATES OF AMERICA
hatle@cpp.edu or ahlephan@yahoo.com http://www.cpp.edu/~hatle

Abstract – The paper presents a new fault location isolation and service restoration (FLISR) scheme, as well as a design and construction of a simulation board where the FLISR scheme is implemented and tested using a DC scaled power distribution system. Testing with different fault locations and load levels shows that the FLISR scheme works effectively. The system can automatically detect faults on distribution feeders, isolate them, and distribute affected loads to neighboring circuits. The simulation may be used to test diverse FLISR schemes. In addition, the scaled model may allow for replication in larger models to be implemented into real-world power distribution systems. Furthermore, the simulation board is useful as an interactive training and public education tool for FLISR schemes, as well as for smart grid concepts of sensor, microcontroller-based control, and automation.

Keywords: Fault location isolation, microcontroller, power distribution, service restoration, smart grid.

1. Introduction

Modernization of power distribution systems is a crucial step to make smart electrical grids. Some of the most important issues concerning the distribution systems include improving their reliability and resiliency. It is highly desirable that the systems can quickly recover from fault conditions and restore power to customers, as well as quickly adapt to changing power demand. Efforts have been made to improve the distribution systems where advanced communication, monitoring and control technologies have been deployed. For example, Power Line Communications (PLC) allows data to be retrieved from the consumer side to the substation or generation side. PLC has been utilized in systems such as Neighborhood/Field area networks (NAN/FAN) and was determined to be cost-effective. Along with communicative devices, self-data-monitoring and control also plays a primary role in making smart grids. The technologies, for instance, support smart substations. A smart substation has the ability to control and monitor the grid real-time data. Ethernet technology and open communication standard IEC 61850 allows the implementation of substation data control [1] [2] [3] [4] [5] [6].

With implementations of communication into the smart grid, newer methods of service restoration come into play. In [7] the increasing need for a fully automated service restoration function after fault events was emphasized. A smart grid would instantly respond to fault detection using automated corrective actions, eliminating the unreliability and inefficiency of human operators. Investigators in [8] proposed the multiagent system (MAS) approach in a fault location isolation and service restoration (FLISR) scheme. The MAS was tested using a DC grid. The results show that the MAS algorithm produced successful restorations and balanced substation loads. As suggested by other studies [9] [10] [11], since power outages are unpredictable and inevitable, FLISR schemes are desirable and implementable with advanced sensing and communication technologies. They would shorten down time caused by the power outages which enhance resiliency of power systems and greatly benefit customers.

Other notable studies concerning power distribution systems include power flow analysis using IEEE 30-bus distribution system, interline power flow controller for limiting the short circuit current in low voltage distribution system, techniques for identifying open and short circuit sections, and determination of fault features in power distribution systems [24] [25] [26] [27] [28].

Problem of consideration:

In this research, we investigate a FLISR scheme which automatically identifies fault location on a distribution feeder, isolates the fault, and changes topology of the feeder to restore power to customers. The motivation for focusing on the FLISR scheme is that it is capable to improve the reliability and resiliency of distribution systems in a substantial manner. The main objectives of the study are:

1) To develop a new FLISR scheme
2) To validate the FLISR scheme using a simulation board.

The advantages of validating the FLISR scheme using a simulation board are: (a) it reduces cost compared to testing such scheme on a real-world system and (b) it is flexible in enabling diverse testing scenarios which can be set up using the board.

In our study, the FLISR scheme is implemented and tested using a simulation board with an automatically-controlled DC power distribution system. The board represents the system feeders using color coded LED strips. The LED strips indicate fault locations and feeder reconfiguration effectiveness. A control algorithm is developed which handles different fault scenarios and restores power to a portion or portions of un-faulted circuits. Once a fault is isolated, the system considers power consumption from nearby circuits and determines which circuit is capable to supply the impacted load(s) and performs relay switching accordingly. In the feeder, relay boards are used as Remote Automatic Reclosers (RAR) which are currently used in power industry to isolate faulted sections of a circuit [12].

The simulation board provides further understanding of the FLISR scheme from both theoretical and hardware implementation viewpoints. Its swift fault identification and power restoration capability shows how the grid self-healing ability can be improved. In addition, the board serves as an interactive education tool of smart grid for technicians and the public.

At the time of this writing, the board has been donated to Southern California Edison (SCE), a large electric utility in California, and is being used by the company for training and public education purposes. It helps SCE raise the public awareness and approval for the company efforts in modernization of its power grid.

2. Theoretical consideration

A number of studies related to fault detection isolation and service restoration in power grids are considered, namely [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23]. Noticeable FLISR schemes include 1.5, 2.5, and 3.5 which aim to isolate faults and recover as much of a circuit as possible The schemes are based on the circuit loading and available tie circuits on the system. We focus on 1.5 and 3.5 schemes.

In a 1.5 scheme (Fig 1), when a circuit breaker trips due to a fault, the existing automation opens the remote recloser at the circuit midpoint then re-energizes the circuit. If the fault is still detected, the circuit breaker trips again and the fault is determined to be located on the first half of the circuit. If the fault is not detected the circuit stays energized and the fault is determined to be on the second half of the circuit.

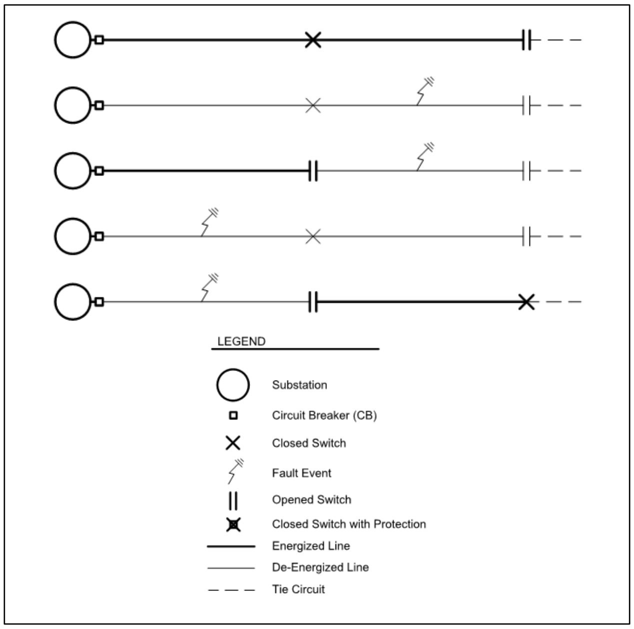

Fig. 1 1.5 automation scheme

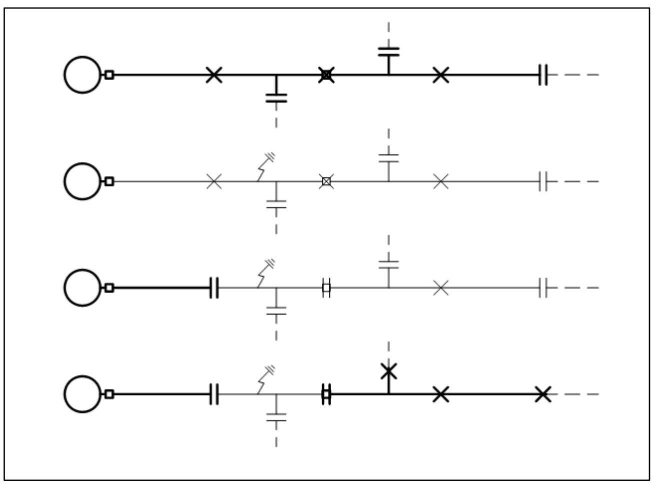

Fig. 2 3.5 automation scheme

When a fault is upstream of the automated switch, the second half of the circuit (i.e. downstream portion) has the potential to be picked up by neighboring circuit(s). If a fault is downstream of the midpoint switch, the fault is isolated by opening the midpoint switch, allowing the upstream portion to be recovered.

In a 3.5 scheme (Fig. 2) a protection device is located at the midpoint of the circuit and the fault detection process takes place at the midpoint if that device detects a fault. This system works with some degree of safety concern as one has to re-energize a potentially faulted power line to find the fault location. This has two drawbacks, safety and damage to the system. Regarding safety, if a faulted line is re-energized there is an increased risk of injury and death to people near the fault [17] [18]. Second, every time one re-energizes a faulted line, an overloaded situation occurs, potentially damaging the grid.

From the analysis, we aims to develop a new FLISR control algorithm to improve the 1.5 and 3.5 schemes discussed above. The details are presented in the following section. It is recognized that future designs should replace all switches with protective devices allowing fault isolation and grid recovery to take place faster. This eliminates the need to open and close circuit breakers and energize the circuit to locate the fault. The largest hurdle for this implementation is higher cost.

3. Control algorithm

The control algorithm is illustrated in Fig. 3 and Fig. 4 where the logic is developed based on the theoretical design analysis. The control algorithm includes two sets of logic. One is for fault location and isolation and the other is for load balancing. The coding language used for implementing the control algorithm is Python 3.0 on microcontroller Raspberry Pi 3 B+. Python is chosen because of its high use in industry and its adaptability.

Fault isolation logic: From Fig. 3, fault conditions are handled based on data pulled from current sensors located at the circuit breaker and the midpoint switch on each circuit. If the midpoint sensor reads a current of sufficiently high magnitude to be considered a fault (fault current), the midpoint switch (MID) opens. Following this event, the furthest closed switch on the circuit also opens to attempt to locate and isolate the fault. The midpoint switch is then reclosed.

If no fault current exists, then the fault location is beyond the closest open switch and is isolated. If there is still fault current at the midpoint, then the midpoint switch will open again, and the fault has been located after the circuit midpoint, but before the closest open switch. The back section can then be picked up by a tie if one exists and loading permits.

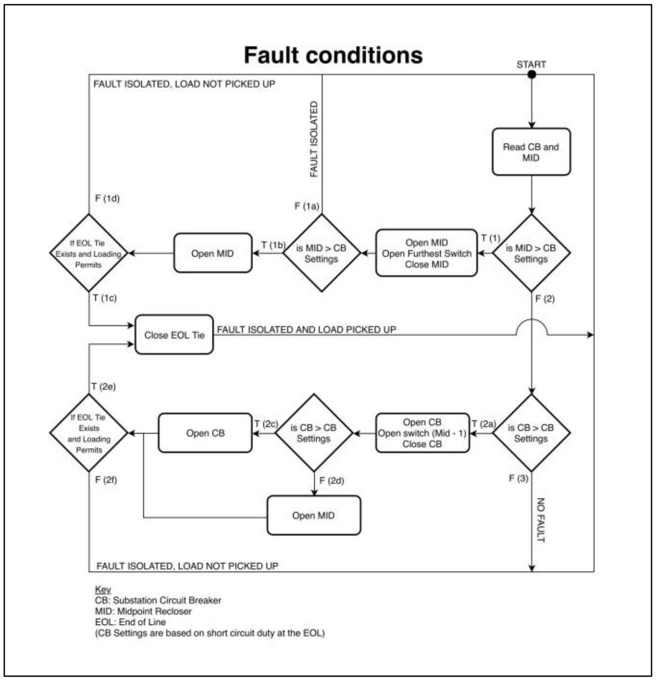

Fig. 3 Flowchart logic for fault location and isolation along a circuit

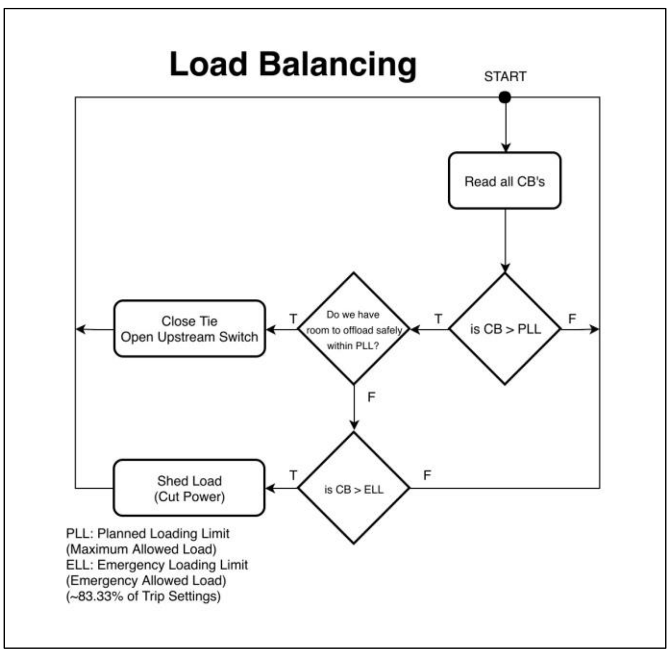

Fig. 4 Flowchart logic for load balancing along a circuit during fault events

If the fault current does not occur at the midpoint, but is read by the circuit breaker, then the fault exists on the front half of the circuit. The circuit breaker and the switch before the midpoint are opened. The circuit breaker is then closed and if no fault current exists, then the fault is located between the midpoint and the switch before it. The back-half of the circuit (past the midpoint), can then be picked up by adjacent circuits if loading permits. If the fault current does exist, then the circuit breaker will open, and the fault has been located and isolated. The back-half of the circuit and the section before the midpoint can be picked up by circuit ties if loading permits.

Load balancing logic: From Fig. 4, load balancing is handled based on data pulled from sensors at the circuit breakers on each circuit. If the circuit breaker reads more than its assigned Planned Loading Limit (PLL), then neighboring circuits will be assessed to see if they can handle the load on the back-half of the overloaded circuit. If multiple neighboring circuits can pick up the overloaded circuits back-half, the neighboring circuit with the lowest loading will receive the load. Load balancing is performed to ensure appropriate loading levels of all circuits fed from the same substation.

Sometimes all neighboring circuits are heavily loaded so they cannot pick up the load from the overloaded circuit. Then, the only option is to shed load. The principle to shed load is dropping non-critical customers on the overloaded circuit to ensure power supply to essential customers such as hospitals and airports. This is the principle that, we believe, is appropriate for load shedding. It is recognized that, in reality, power utilities likely have different load shedding methods.

Advantages of proposed control algorithm:

1) It allows a distribution feeder (i.e. a circuit line on the simulation board) to be sectionalized into many sections using remote-controlled switches. This reduces fault-isolated area and in turn, the number of customers being affected.
2) Smaller sections likely facilitate load balancing as it is easier for a neighboring circuit to pick up a small portion of an affected circuit (i.e. lower load being transferred).

More details of the fault isolation and load balancing logic are provided in the following pseudo codes.

Pseudo code for Fault Location and Isolation logic in Fig. 3

START. A current sensor will read the amperage running through the CB and midpoint switch.

1. If the midpoint reads greater than the CB settings, a fault is present. The midpoint and furthest switch downstream will open. The midpoint will re-close to test if fault still exists. A current sensor will read the amperage running through the midpoint.

1a. If the midpoint reads less than the CB settings, then the fault is determined to be located after the furthest switch downstream and is considered to be isolated.

1b. If midpoint reads greater than the CB settings, the midpoint will open and isolate the fault.

1c. If the EOL tie exists and permits the remaining load, then the tie will be closed to pick up the additional circuit.

1d. If loading does not permit, then the remaining load is not picked up.

START. A current sensor will read the amperage running through the CB and midpoint switch.

2. If the midpoint reads less than the CB settings, then a check will be performed on the CB.

2a. If the CB reads greater than the CB settings, then the CB and the switch before the midpoint will open. The CB will close and the current sensor will test for a reading of greater than the CB settings.

2c. If the CB reads greater than the CB settings, then the CB will open.

2d. If the CB reads less than the CB settings, the midpoint will open.

2e. (2c or 2d have been performed) If the EOL tie exists and permits the remaining load, then the tie will be closed to pick up the additional circuit.

2f. (2c or 2d have been performed) If loading does not permit, then the fault is isolated, then the remaining load is not picked up.

START. A current sensor will read the amperage running through the CB and midpoint switch.

3. If neither the midpoint switch nor the CB show greater than the CB settings, then a fault is not present.

START. Readings will continue until midpoint or CB is greater than the CB settings.

Pseudo code for Load Balancing logic in Fig. 4

START. A current sensor will read the amperage running through all CBs.

If the CB reads amps above its PLL, a check is performed to see if the neighboring circuit can pick up the additional load while remaining under its PLL.

If the neighboring circuit passes the previous check, the tie between the circuits will be closed and the upstream switch will open, picking up a section of the neighboring circuit.

If the previous check fails, a check is performed to see if the CB is within its ELL.

If ELL check fails, load is shed by cutting power to consumers.

If the CB reads amps within its PLL and ELL, then the circuit is not overloaded.

START. Readings will continue until CB reads above its PLL.

4. Distribution system design and component data

The distribution system design is shown in Fig. 5. It has 4 feeders which are supplied from a substation. The distribution system model simulates a typical grid within a community. It delivers power to different groups of residential, industrial, commercial, and mixed (commercial and residential). The system is designed with realistic data (load, lines, substation etc.) then scaled down for implementation in the simulation board.

In the simulation board (Fig. 5), the branches are represented using LED strips (orange/yellow, blue/greenish, purple, and red). The system has 18 controlled switches, which are closed and opened appropriately to segregate the different groups within the community. The segregation is for efficient power distribution based on required customer demand under normal and fault conditions.

Loads: Apart from the LED strips, other loads used in the simulation board include four fans, four potentiometers (for adjusting loads along a circuit during simulation), and four light bulbs. The fans are

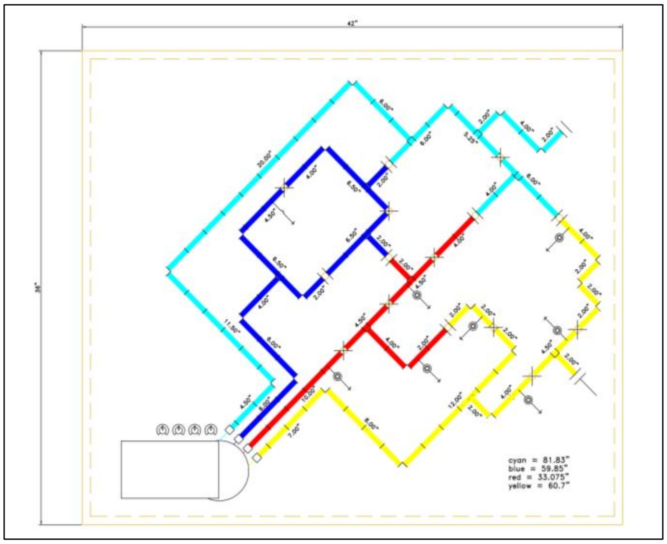

Fig. 5 Layout of 4-circuit distribution system

Note: In Fig. 5, cross sign (X) = normally-closed switch; parallel sign (| |) = normally-open switch; square sign (☐) = circuit breaker; Round signs near LCD screen in the bottom left corner are 4 potentiometer switches for varying load on each of 4 power lines.

Table 1 Component load datasheet

	BULB	FAN	POT	LED
POWER [W]	5	1.44	25	0.38 (per in.)
CURRENT [A]	0.42	0.12	1.2	
VOLTAGE [V]	12	12	12	12
RESISTANCE [Ω]	28.34	100	10	
CURRENT [A]			1.58	

Note: Table 1 provides specification of the loads used in the simulation board, namely, bulb, fan, potentiometer, and LED strips.

Table 2 Circuit line load calculation

ORANGE	O1	O2	O3	O4	
LENGTH [in]	35	4	6	10	
LED [A]	1.1	0.13	0.19	0.32	
LOADS	FAN	BULB	POT	BULB	
	0.12	0.42	1.2	0.42	
TOTAL [A]	1.22	0.55	1.39	0.74	**3.91**

Note: Load current calculation for Orange/Yellow power line (4th line counted from top to bottom in Fig. 5)

BLUE	B1	B2	B3	
LENGTH [in]	29	8	12	
LED [A]	0.93	0.25	0.39	
LOADS	BULB	POT	FAN	
	0.42	1.2	0.12	
TOTAL [A]	1.36	1.46	0.51	**3.33**

Note: Load current calculation for Blue/Greenish power line (1st line counted from top to bottom in Fig. 5)

PURPLE	P1	P2	P3	P4	
LENGTH [in]	10	12	6	4	
LED [A]	0.32	0.39	0.19	0.13	
LOADS		POT		FAN	
		1.2		0.12	
TOTAL [A]	0.33	1.59	0.19	0.25	**2.34**

Note: Load current calculation for Purple power line (2nd line with the rectangular loop, counted from top to bottom in Fig. 5)

GREEN [A]	G1	G2	G3	
LENGTH [in]	35	25	10	
LED [A]	1.13	0.81	0.32	
LOADS		BULB		
		0.42		
TOTAL [A]	1.13	1.23	0.32	**2.69**

Note: Load current calculation for Red power line (3rd line counted from top to bottom in Fig. 5)

mounted along the sides of the board box to act as loads, as well as for cooling other devices located inside the board box.

Load power consumption: The system load power consumption is calculated based on the rated amperage of load components which are shown in Table 1. This also includes the power consumption of the LED strips that are placed throughout the board to represent the circuit lines. Table 2 shows the data for each feeder based on the loads placed along the power line. Using the load calculations for individual components and circuit topology, scenarios are created to simulate fault situations and power restoration process. The calculated total current is 12.27 A. The load components and the LED strips are placed and wired in parallel. Detailed circuit layout configurations are provided in Appendix.

5. Construction of simulation board

The board construction is shown in figures 6 through 9.

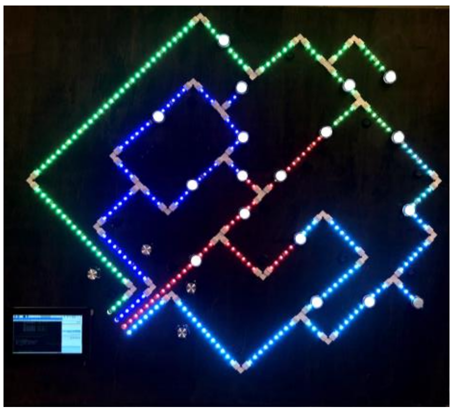

Fig. 6 Board top view with LED strips, light indicators, switches, potentiometer knobs, and LCD screen

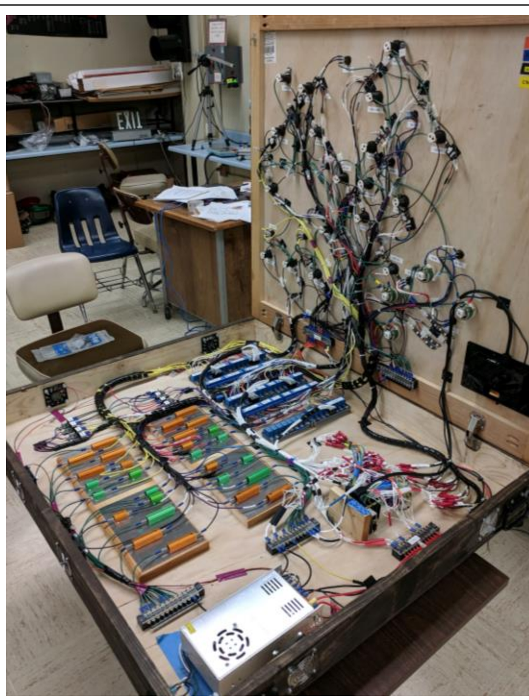

Fig. 7 Overall inside view of completed board

To house the components of the simulation board, a 3 feet by 4 feet wooden box is constructed with two cabinet latches installed along the inside of the box to secure the lid when closing. The exterior of the box is painted for aesthetic purposes. Four handles are installed outside of the box for transportation and carrying purposes.

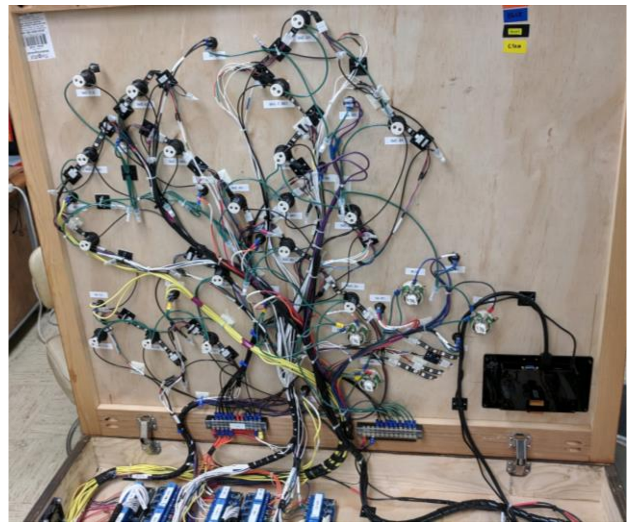

Fig. 8 Board inside view showing connections of components on top with inside components

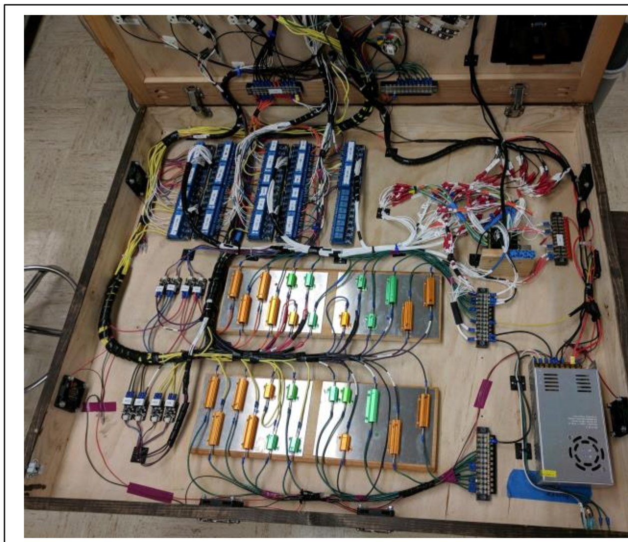

Fig. 9 Board inside view showing resistors, relay boards, buses, current sensors, cooling fans, microcontroller with expansion I/O ports, and power supply.

The inside of the box is accessible through the attachment of a piano hinge connecting one side of the box to the top piece of plywood where the four LED strips are placed. The top of the box also includes 18 LED indicators, where a lighted indicator represents a closed switch along the circuit, while an unlit indicator represents an open switch to segregate the different load types.

There are 12 rocker switches that are used to create a fault along a portion of a power line. Four knobs are used to adjust potentiometers to create varying loads along each of the four circuits. A 7-inch LCD screen provides a graphical user interface (GUI) that displays the amount of amperage flowing through each circuit and statements explaining the real time simulation processing. The rocker switches and LED indicators laid out on the top of the board are connected using 16 GA wires while the RGB LED strips are connected using 22 GA wires. The box also includes other components such as resistors, 10 8-channel relay boards, four cooling fans, five buses, eight current sensors, one Raspberry Pi 3 B+ with I/O expansion boards, a 12-V power supply, and a 12-V to 5-V DC to DC buck converter.

The list of the components and cost is provided in Appendix.

6. Testing of simulation board

The test aims to observe if the developed automatic fault location, isolation, and service restoration (FLISR) scheme works properly.

Test setting:

- A fault is induced using a switch on one of the four circuit lines (feeders). The board has 12 switches for creating a fault in different locations (see Section 5). A current sensor will read the value of the fault current running through the circuit breaker and the midpoint switch. Based on the sensed fault current value, the microcontroller will execute the control algorithm (see Section 3) and switch appropriate relays to isolate the fault and distribute the affected loads (i.e. circuit portions) to neighboring healthy circuit(s).
- Various tests are performed on each of the four circuit lines with different fault locations and different loading levels. The board has 4 potentiometer switches for varying load on each of the 4 circuits (see Section 5).
- To facilitate observation, the control program is set to allow roughly one second to perform a task (e.g. reading of a fault current value or activating a relay is considered a task). Current values are multiplied before outputting to the LCD display. This is to represent realistic fault situations.

Testing results:

Figure 10 shows the data collected from running a test fault along the red circuit. It can be observed that, at the beginning, the load current is sensed to be 200A (the value goes through a multiplier before displaying). At time of around 1.4 seconds, a current sensor detects a surge current of around 550A.

The 550-A current indicates that there is a fault occurring in the circuit. The automation scheme of the board begins shutting the circuit down, where the load current becomes zero. Time is given for the microcontroller to validate and test the programmed logic to determine the next action.

Before distributing the affected loads, the control program allows for the fault current to briefly return onto the power line for a second for verification reading (i.e. to read the fault current again and confirm that the reading is correct). Then, the control program activates appropriate relays to isolate the fault and distribute affected loads to neighboring circuits. After these tasks

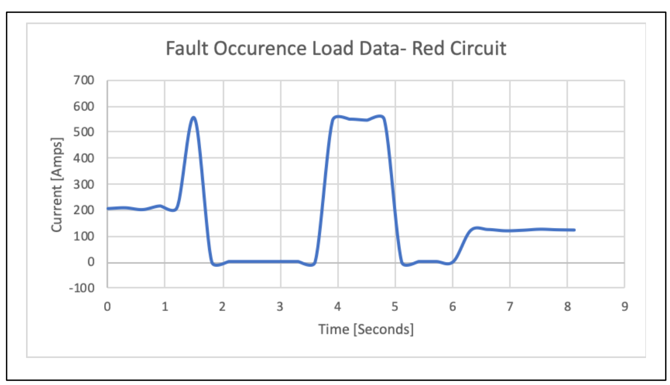

Fig. 10 Current along red circuit when a switch creates a fault (Shown value is multiplied)

are completed, the load current of the affected circuit is reduced to 100A (because a part of the original load has been isolated and a part has been transferred to a neighboring circuit).

The amount of time for the FLISR process is set in a way so that the overall simulation time is slightly under 10 seconds for demonstration purposes. In real-world situations timing would greatly depend on the specification and capability of protection equipment installed along the circuits. The realistic timing of the FLISR process would be shorter. For example, it typically takes a circuit breaker around 5-7 cycles (83-117ms in a 60-Hz power system) to detect a fault current and trip to clear the fault.

Overall, diverse tests are performed on all the four circuits with different fault locations and different loading levels. The results show that the implemented FLISR scheme works effectively to isolate the faults and distribute affected loads (circuit portions) to neighboring circuits.

7. Conclusion

In this study, a new fault location isolation and service restoration (FLISR) scheme is developed. In addition, a simulation board is designed and constructed for testing the FLISR scheme. The simulation board is a DC-based scaled model of a power distribution grid where the FLISR scheme is implemented in an automatic manner. The testing results have led to following conclusion:

1) Testing of the physical model shows that it works properly. This, in turns, proves that the theoretical design is correct.

2) Tests are performed on the system four circuits with different fault locations and loading levels. The results show that the FLISR scheme works effectively. It can accurately detect the faults, isolate them, and distribute affected loads to neighboring circuits.

In terms of broader impacts, the contribution of this study is as follows:

1) The simulation board may be used to test different FLISR schemes. One needs to program a FLISR scheme of consideration in the board microcontroller to test it. The advantages of the testing using the simulation board include: (a) reduction in testing cost compared to testing such schemes on a real-world grid and (b) flexibility in setting diverse testing scenarios.

2) The scaled distribution system model of the board may allow for replication in larger models to be implemented into real-world power distribution systems.

3) The simulation board is helpful as an interactive training and public education tool for FLISR schemes, as well as for smart grid concepts of sensor, microcontroller-based control, and automation.

4) The simulation board provides further understanding of the FLISR scheme from both theoretical and hardware implementation viewpoints. Its swift fault identification and power restoration capability shows how the grid reliability and self-healing ability can be enhanced.

In terms of future work, due to project time constraints, the load balancing logic is not fully implemented in the simulation board. A future work is to improve the load balancing logic. Furthermore, it is desirable to change the DC-based circuits in the existing simulation board to AC circuits. The AC circuits would represent real-world power distribution systems better.

Appendix

A. Circuit design

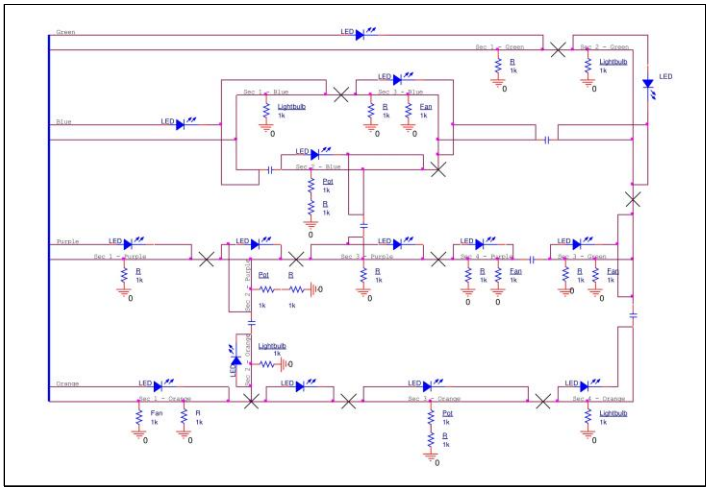

Fig. 11 PSpice one-line diagram of board circuits with loads and LED strips

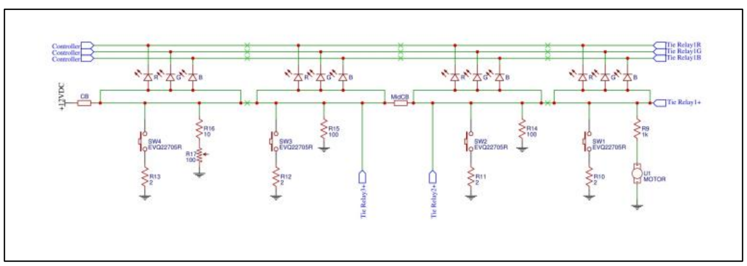

Fig. 12 PSpice one-line diagram of board with microcontrollers and relays (CB)

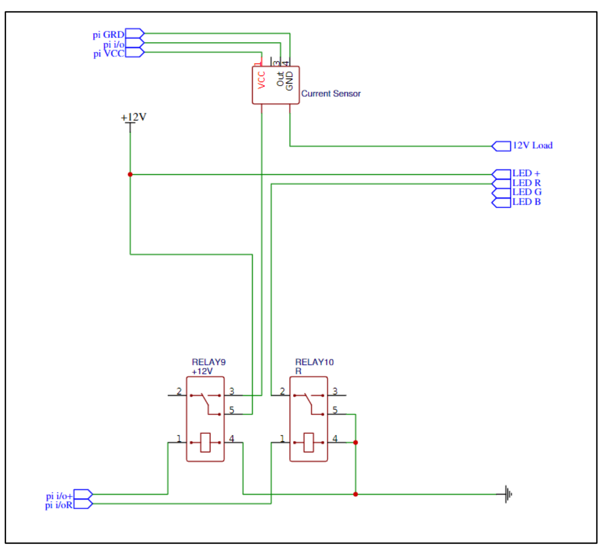

Fig. 13 PSpice one-line diagram of board with microcontrollers and relays (RSR/MID)

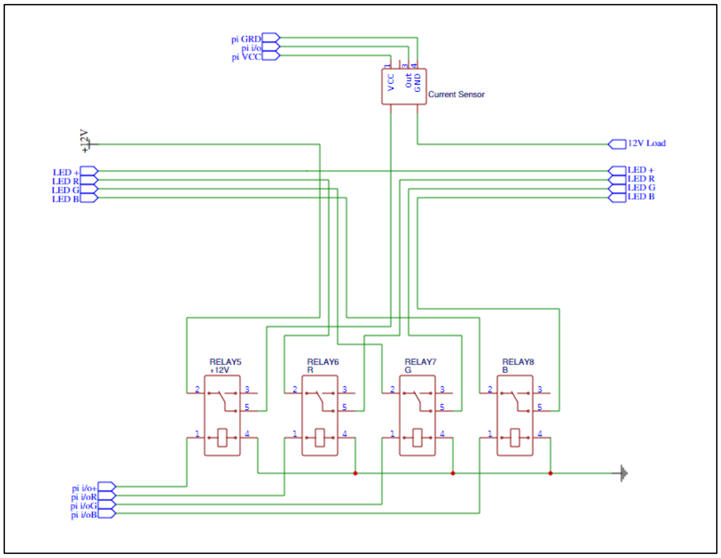

Fig. 14 PSpice one-line diagram of board with microcontrollers and relays (RCS)

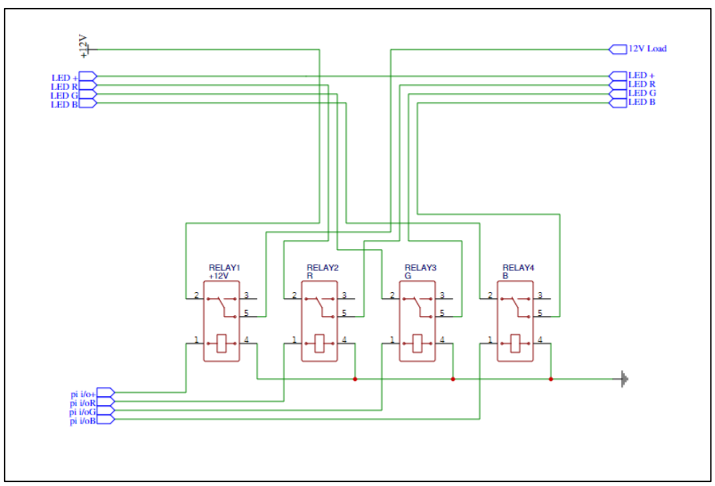

Fig. 15 PSpice one-line diagram of LED, Raspberry Pi microcontroller, and relay connections

B. List of components and cost

Table 3 List of components and cost

PART	QUANTITY	PRICE/UNIT	TOTAL
POWER SUPPLY	1	$20.00	**$20.00**
AC TO DC CONVERTER	1	$23.95	**$23.95**
SOCKET & CORD	1	$13.00	**$13.00**
LCD SCREEN	1	$80.00	**$80.00**
HDMI	1	$6.99	**$6.99**
KEYBOARD	1	$16.99	**$16.99**
RASPBERRY PI 3 B+	1	$35.00	**$35.00**
I/O EXPANSION BOARD	3	$21.00	**$63.00**
SD CARD	1	$11.99	**$11.99**
8 CHANNEL DC RELAY BOARD	10	$8.98	**$89.80**
CURRENT SENSOR	8	$9.95	**$79.60**
25 W 100 OHM POTENTIOMETER	2	$16.99	**$33.98**
100 W 2 OHM RESISTOR	2	$4.00	**$8.00**
25 W 1K OHM RESISTOR	2	$3.50	**$7.00**
25 W 100 OHM RESISTOR	3	$2.85	**$8.56**
25 W 50 OHM RESISTOR	10	$1.66	**$16.60**
25 W 10 OHM RESISTOR	3	$3.42	**$10.26**
22 GA WIRE	1	$17.00	**$17.00**
16 GA WIRE	1	$29.20	**$29.20**
ROCKER SWITCH	12	$6.78	**$6.78**
LED INDICATOR	16	$3.67	**$58.72**
12V TO 5V DC CONVERTER	1	$7.99	**$7.99**
IN LINE FUSE	1	$6.29	**$6.29**
FAN	4	$7.99	**$47.94**
LED RGB STRIP	3	$17.31	**$51.95**
LED T CONNECTORS	20	$8.89	**$8.89**
LED L CONNECTORS	20	$8.89	**$8.89**
4 PIN LED CONNECTOR	50	$19.99	**$19.99**
LED RGB CONTROLLER	1	$40.00	**$40.00**
PIN HEADERS	1	$10.99	**$10.99**
BUSES	4	$3.49	**$13.99**

4 PIN JUMP WIRE	1	$6.99	**$6.99**
BULLET CONNECTORS	3	$7.69	**$23.07**
STANDOFFS	1	$5.99	**$5.99**
HINGE	1	$16.98	**$16.98**
1X4X8 WOOD	2	$5.00	**$10.00**
¼ PLYWOOD	2	$14.00	**$28.00**
GRAND TOTAL			**$944.37**
**Does not include prices of tools purchased for project*			

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