Predictive Power Flow Simulator for SCADA Systems—A Real-World Implementation

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***Abstract*—A power system is a sensitive network, requiring precise control and monitoring. Many industries deploy a central supervisory control and data acquisition (SCADA) system to monitor and control the facility, including utilities, manufacturing, infrastructure, and process control plants. The SCADA system collects real-time data from the machinery, sensors, and intelligent electronic devices (IEDs) in the field and displays them on a monitor through the human-machine interface (HMI), supporting the operator(s) in making informed decisions.**

This paper discusses the real-world implementation of a power flow simulator, which is designed using IEC 61131-3 and runs on a substation-hardened automation controller. This simulator provides the operator with an intuitive HMI, through which the operator can visualize the present state of the power system based on real-time data gathered from field IEDs, as well as see a snapshot the power system at any given instant. The operator can then use this information as the initial condition for simulation. Once an initial condition is selected, the operator can simulate their desired switching operations to understand the steady-state impacts on the power system and its consequence on the process, and then, based on the steady-state results generated by the simulator, can make an informed decision on whether to proceed with a desired action.

***Keywords*—IEC 61131-3, Maintenance, Operation, Power System, SCADA, Simulator**

I. Introduction

Modern power systems have become extremely complex with the increasing demand for electrical power. Large industries, due to current competition, have adapted to use onsite energy resources to ensure higher availability of electric power to their plants and maintain system uptime. Because of this increasing complexity, it has become necessary to improve digital infrastructure in order to better monitor and control these systems.

The SCADA system has been adopted in various industries to visualize and control the power system with a bird's eye view, allowing for systemwide assessments. The SCADA systems are now capable of running on Microsoft Windows, Linux, UNIX, and even cloud-based platforms. A SCADA system is defined as an integrated control system comprised of computers, controllers, field devices, and sensors, which assists the operator in monitoring and controlling the plant from a remote or central location.

Though these SCADA systems allow the operator to control the system equipment from afar, an incorrect switching operation can lead to the power failure of an entire plant due to the cascading effect and highly volatile nature, of electrical energy. Therefore, it has become a necessity in the current era to avoid such catastrophic mistakes. Thus, the concept of using an online simulator to capture data and perform operations in a controlled environment is becoming increasingly popular.

A simulator is defined as a device used to mimic real world systems in a controlled environment for understanding and/or predicting the behaviour of the system. A simulation can be defined as the process of imitating a system [1]. Simulators have been increasingly used in the power industry for simulating power system operations, performing analyses and design and, in some cases, testing of the system [2] and [3].

This paper discusses the role of a modern power system simulator, running on an industrial-grade embedded real-time operating system, capable of simultaneous communication and logic processing using IEC 61131-3. Section 2 highlights the limitations associated with traditional power-flow algorithms, followed by Section 3, which presents key and distinguishing features of universal power flow (UPF). Section 4 discusses the system architecture of a typical SCADA system, incorporating the predictive simulator. Section 5 describes the features of the predictive simulator. Section 6 provides details of the user interface to access and operate the simulator. Section 7 describes the power system used for testing, with details of testing scenarios and analyses of results. Section 8 concludes the paper and lists out plans for future work.

II. Limitations of Traditional Power Flow

As stated in [4], traditional power flow algorithms evaluate the flow of a system by making the following assumptions:

- The electrical power system needs a slack bus.
- The load flow is not a function of frequency (frequency is always assumed to be a nominal frequency of 50 or 60 Hz).
- The active power generation is always constant.
- The reactive power control of the generation is used to maintain certain bus voltages.

In islanded systems or microgrids, these assumptions are not always valid, because they usually do not have a strong source performing, as the slack bus and the frequency of their systems are more prone to vary near nominal frequency. Moreover, the active and reactive power control of distributed generators (DGs) could be in various strategies. Keeping in mind these distinct characteristics, the UPF algorithm was developed to cater to industrial systems and microgrids along with any traditional power systems [4] and [5].

III. Features of the UPF Algorithm

The predictive simulator presented in this paper is based on the UPF algorithm. The key features of this algorithm are as follows:

- Handles islanded or grid-connected systems at nominal or off-nominal frequency
- Functions with the following active control modes of DGs, including isochronous, droop, and constant power
- Allows the following reactive power control modes of DGs, including Mvar, power factor (PF), voltage, and voltage droop
- Solves the load flow without a slack bus and can provide voltage magnitude and angle for each bus and active and reactive power flow for each branch
- Accepts the MW and Mvar limitations of all DG units
- Evaluates system frequency
- Works with frequency-dependent active-power loads
- Handles voltage-dependent reactive-power loads
- Solves multiple islands simultaneously
- Permits any number of buses and is only limited by the hardware and speed

IV. Simplified System Architecture for Predictive Simulator

Modern IEDs provide interfaces for communications to report data and accept control commands from the operators. Field IEDs are connected to the SCADA system and the predictive simulator via a communications network, based on ethernet switches.

The field IEDs report data to the SCADA and predictive simulator over the Distributed Network Protocol (DNP3). These IEDs share data to the respective devices, using independent DNP3 data maps.

The simulator and the SCADA system operate independently. The simulator has its own independent communications processor, logic engine, visualization engine, and memory, allowing it to be used even when the SCADA master goes offline.

These data collected by the simulator can be viewed on the HMI screen of the simulator, which resides in the simulator visualization engine. These data, or a snapshot of data, can be captured and stored in the memory of the simulator. These captured data can be used to perform operational scenarios, using logic written within the simulator. Refer to Figure 1 for simplified system architecture of the proposed simulator.

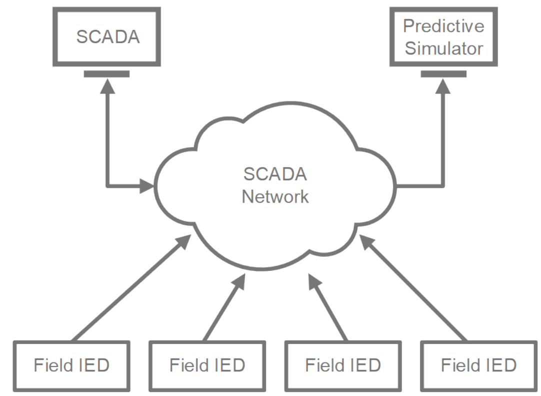

Figure 1 – Connection to SCADA master and predictive simulator

V. Features of Predictive Simulator

The predictive simulator presented in this paper is based on the UPF algorithm described in [4]. Using the UPF algorithm, the predictive simulator is designed such that it receives real-time analog measurements and breaker statuses from the field IEDs and populates those on the HMI screen. The HMI screen has been designed in the form of a one-line diagram (one-line), which is illustrated in figures later in the paper.

This design provides a platform for the user (plant operator or maintenance engineer) to perform offline load-flow analysis and observe voltage profiles, assisting the user in making switching decisions for the power system.

The user is provided with a save control button on the HMI screen to save the present power system state at any given time. To execute the simulation scenario, the user can press the load control button on the HMI screen and the saved power system state can be activated as the initial conditions for the simulator. The user can now perform breaker switching operations—changing load values, changing mode of generators, etc.—and analyse the results of the actions to make an informed decision whether such sequences of operation can be executed on the live power system or not.

The usual requirements to implement a predictive simulator, using UPF, include the following:

- Active power, reactive power, voltage, and frequency measurements associated with each circuit breaker/bus
- 52a and 52b status for each circuit breaker
- Active power, reactive power, and voltage measurements associated with utility connection
- Active power, reactive power, and voltage measurements associated with each generator
- Data sheets for all transformers that include, but are not limited to, power rating, impedance, and primary and secondary voltage ratings
- Data sheets for all cables/transmission lines and conductors
- Operating modes for all generators, such as isochronous, droop, constant power, etc.
- Tap changer details for all transformers, including the maximum and minimum step size and whether they are online or offline

VI. User Interface

The simulator features a local visualization engine to display the collected data of the system on the HMI screen. The HMI can be accessed using any local web browser and does not need any special software to visualize the system. This saves space as well as allowing computations to happen in real-time, since the logic engine and visualization are on the same processor.

The HMI consists of separate screens to visualize and analyse data. The live data captured can be viewed on the HMI one-line screen in order to monitor the current state of the power system. The HMI interface also enables the operator to send commands from the same screen as well as alter the power system topology.

The live data displayed on the screen can be captured and stored in the memory of the simulator. It is also possible to capture more than one set of data values to be used as initial conditions for system analyses.

The captured data can be loaded on a different one-line screen to mimic the power system state the operator intends to change. The operator can perform operations on this screen to verify the impact of these switching operations on the system, using the power system model on the simulator.

VII. Power System Details and Simulation Scenarios

This section briefly describes the power system used for testing the proposed simulator followed by two different scenarios to present the functionality of the simulator.

The power system is connected in 5 buses (with normally closed bus ties), four transformers connected to the utility, one utility connection, and three distributed energy sources (DERs).

The utility is supplying power to the system at 115 kV, and the buses are connected to the utility via transformers 115/12.47 kV. All the buses have a load connected to them.

Figure 2 shows the power system on which an operator is trying to test the voltage, active power, and reactive power variations due to breaker operations.

A. Scenario 1

This scenario describes the systemwide voltage impact due to generator and breaker operation, during a heavy loading condition. As the initial condition, the system is utility-connected and all the DERs are disconnected.

All transformers are loaded between 22 and 25 MW, and all are supplying approximately 15 Mvar to the system buses to maintain voltage to 1 pu. The load connected to Bus 2 is consuming the most amount of power in the system. For this scenario, the breaker between Bus 1 and Bus 2 is under maintenance. Refer to Figure 3.

For the first simulation, the operator switches on Gen 1 and Gen 2 with the governor mode in frequency droop and the exciter mode in voltage droop. Switching on the generators improves voltages on Bus 2, Bus 3, Bus 4, and Bus 5, while reducing the power import via the utility. The power flow across transformer (XFMR) 1 remains same; however, power flow is reduced across other transformers due to power contribution from the generators. Refer to Figure 4.

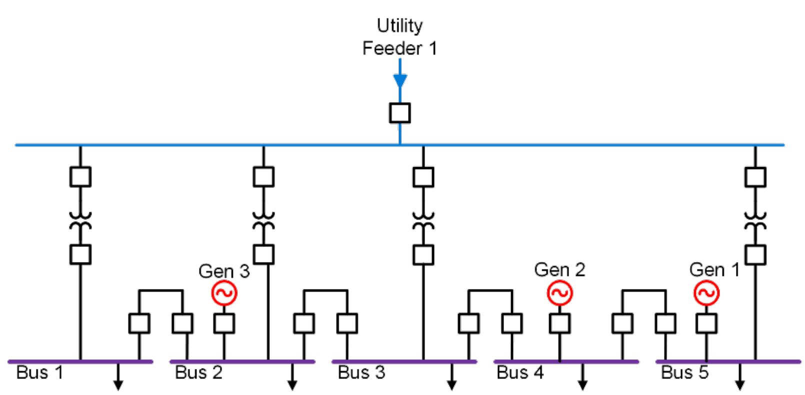

Figure 2 – Example power system

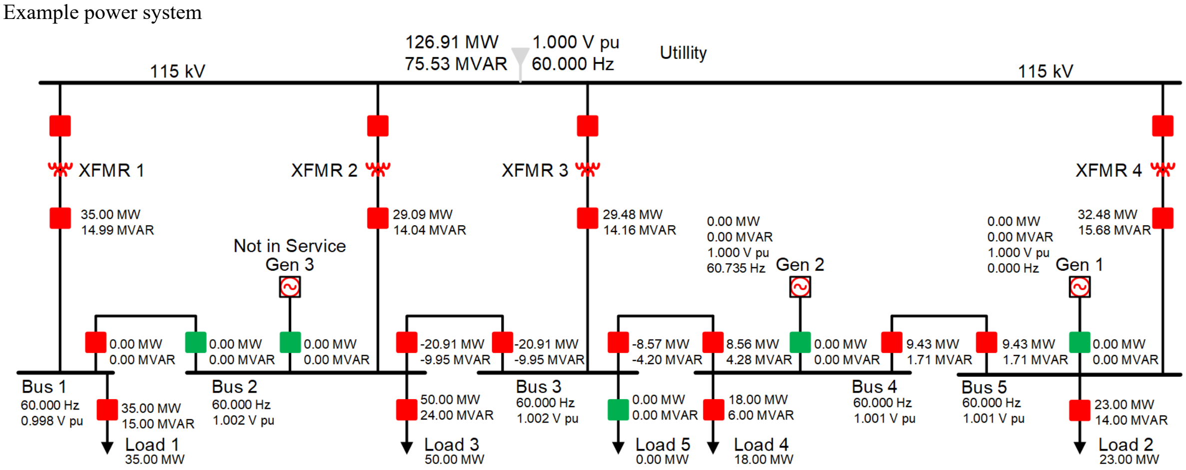

Figure 3 – Power system in heavy loading condition

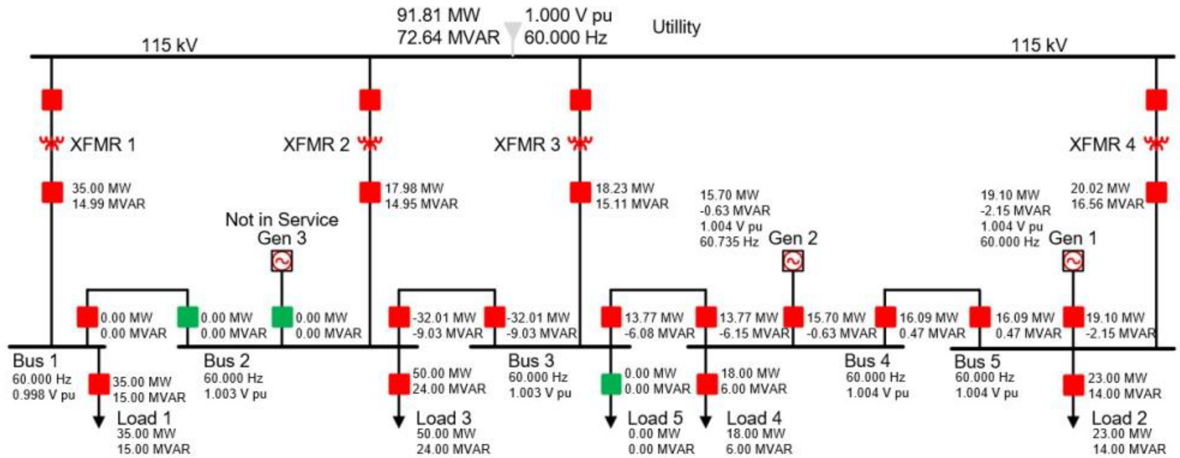

Figure 4 – Power system in heavy loading condition with generators running

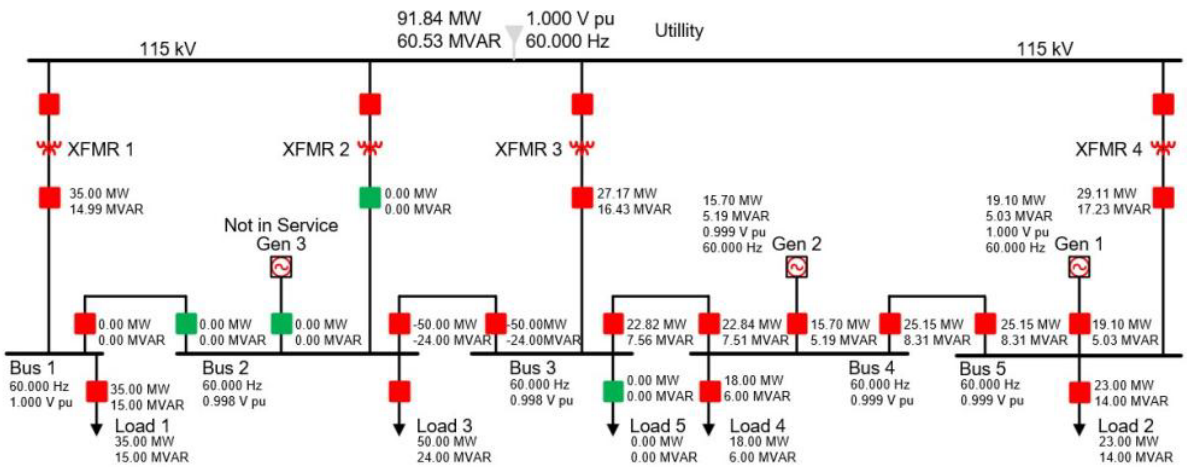

Figure 5 – XMFR 2 breaker open

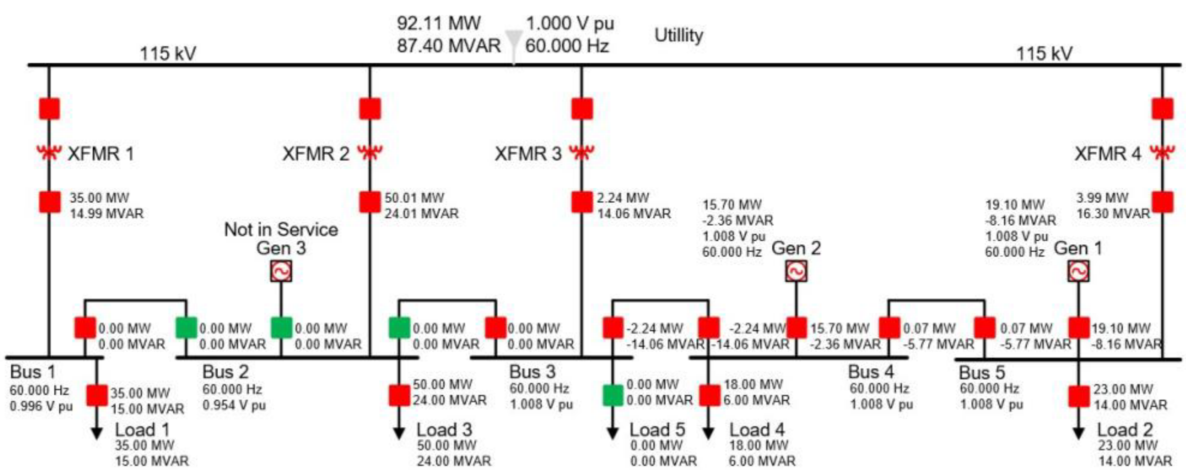

Figure 6 – Breaker between Bus 2 and Bus 3 open

Continuing from the resulting power system state of the first simulation, the operator disconnects XMFR 2 from the system. As a result, the loading of XMFR 3 and 4 increases by approximately 1.5 times. The voltages of Bus 2 and 3 drop to 0.98 pu, while Bus 4 and 5 drop to 0.99 pu. The reactive-power output from the generators is increased to improve the voltage of buses. The voltage at the terminals of the generator is reduced with increased reactive power output showing the droop characteristics of the generator. Refer to Figure 5.

Continuing from the resulting power system state of the second simulation, the operator disconnects the breaker between Bus 2 and Bus 3. As a result, XMFR 2 is heavily loaded, supplying all the power to the load connected to Bus 2. The voltage on Bus 2 drops to 0.95 pu.

The loading on XMFR 3 and XMFR 4 drops to approximately 80 percent of the initial condition, and the voltages on Bus 3, Bus 4, and Bus 5 increase to 1.008 pu. Refer to Figure 6.

To avoid these voltage variations in both the scenarios, the operator can adjust the tap position on the transformer to maintain voltage on all the buses, wait for the breaker maintenance to be completed, or wait for system loading conditions to be improved.

B. Scenario 2

This scenario describes the systemwide voltage impact due to breaker operation during a light loading condition (about 75 percent of system capacity). The utility is the only source of power and all the DERs are disconnected from the system.

XMFR 1, XMFR 2, and XMFR 3 are approximately equally loaded, and XFMR 4 has a slightly higher loading. The load connected to Bus 2 is consuming the highest amount of power. The voltages of all the buses are stable at 1.00 pu. Refer to Figure 7.

For the first simulation, the operator disconnects XMFR 2 from the system. In this scenario, XMFR 1, XMFR 3, and XMFR 4 equally share the load, which XMFR 2 was supplying, and the voltages of Bus 1, Bus 2, Bus 3, Bus 4, and Bus 5 have dropped to 0.988 pu. Refer to Figure 8.

As with the second operational scenario, the operator disconnects the breaker between Bus 2 and Bus 3. The load on XMFR 1 and XMFR 2 increases by approximately 35 percent, while the loading on XMFR 3 and XMFR 4 drops by 35 percent. The voltages on Bus 1 and Bus 2 drop to 0.985 pu, while voltages of Bus 3, Bus 4, and Bus 5 increase to approximately 1.015 pu. Refer to Figure 9.

To avoid these voltage fluctuations, the operator must adjust the tap positions of all the transformers.

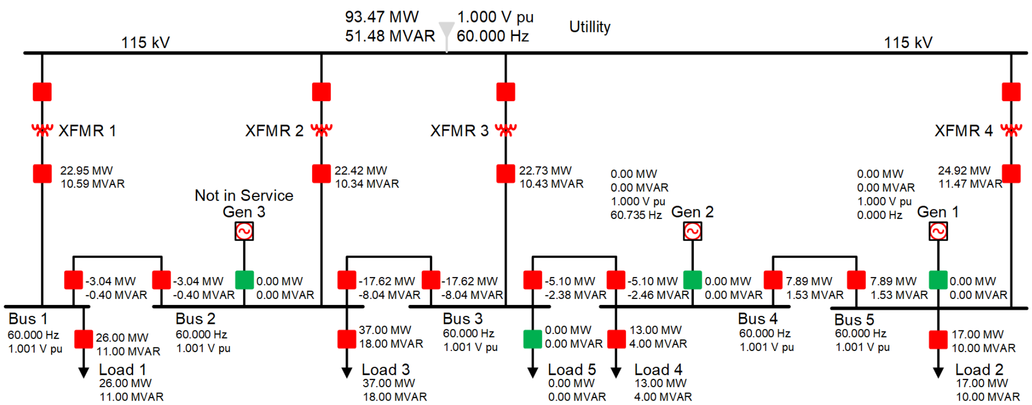

Figure 7 – Power system in light loading condition

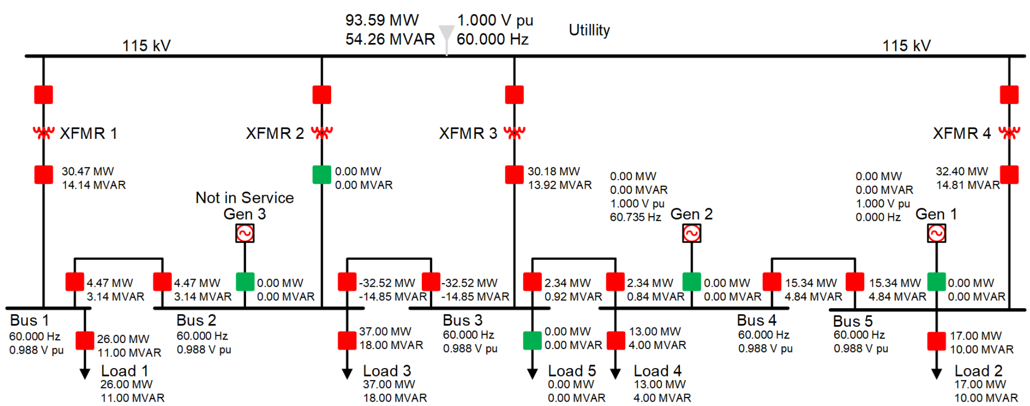

Figure 8 – XMFR 2 breaker open

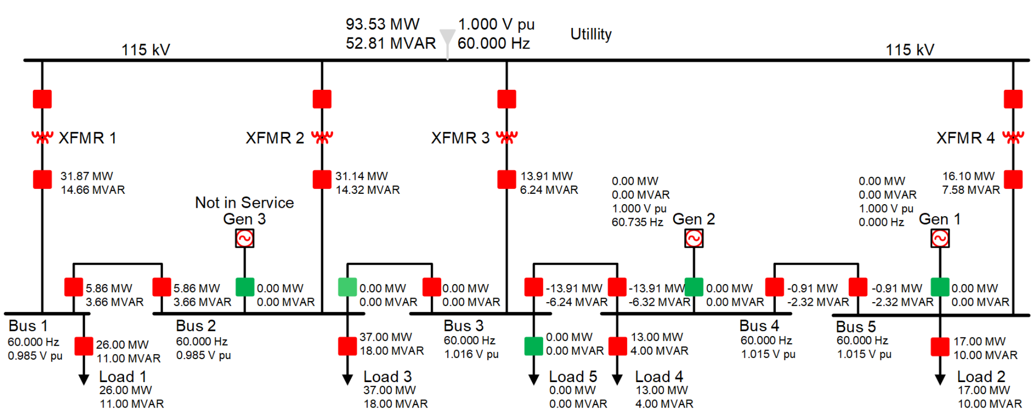

Figure 9 – Breaker between Bus 2 and Bus 3 open

VIII. Conclusion and Future Work

This paper presented a predictive simulator, designed to assist SCADA system operators, electricians, and maintenance staff in simulating their switching decisions, using real-time data to initialize the power system model. And further, it includes how operators can use the results of these simulations to perform more informed and more accurate actions on the real power system. This ensures that misoperations and inadvertent actions can be avoided on a live facility, which can lead to a system disturbance—possibly resulting in a power system blackout.

The authors are planning to build upon on this work to add new features to the predictive simulator, such as generating test reports for each scenario, which can be logged and used as a reference for future maintenance decisions.

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