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Research article

Mitigation of the Impact of Cooling System Failure in a Mobile Switching Center Using an Adaptive Controller

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ABSTRACT

The aim of this research work is to develop an adaptive controller to mitigate the impact of cooling failure in a mobile switching center prefab room(s) during power or cooling failure. Heat build-up inside the telecom room is unavoidable since the cooling systems do not work during a power outage causing rapid rising temperature above ASHREA recommended guideline of 18 to 22oC for optimum performance. This heat if unmanaged during a power loss leads to total or partial services downtime, and as a result, data is lost, customer quality of experience (QoE) is impacted, business reputation is damaged, and revenue is lost. The characterization and simulation results presented in Table 2 and 5 shows that the combined cooling reliability of all the prefab rooms was 58.54% at 744hrs and suggests that only 58.54% of the prefab rooms can sustain cooling after a one-month cycle period. Further checks on the combined cooling reliability gave 83.53% at 250hrs for same failure rate and calls for urgent and stringent maintenance program to be developed for 250hrs cycle and proactively applied to the cooling units on a need basis to improve the reliability of the older units especially during the heat season of the year. This should be in addition to the already existing 744hrs maintenance cycle. Also, the test result of the developed Adaptive controller shows an improvement in MTTR from about 60 mins to < 2 mins and validates the ability of the controller to improve the overall system reliability to 99.982% required for high performance of the switching center and public safety as specified by ANSI/TIA. Lastly, the developed Adaptive controller will mitigate the impact of cooling failure in any of the mobile switching center prefab rooms and can be implemented in any telecommunication room where cooling is critical for optimum operation.

Keywords: *Cooling System Failure; Mobile Switching Center; Adaptive Controller*

Introduction

The government classifies mobile switching centers, data centers, and other communications facilities as critical national infrastructure (CNI) because these facilities' services support the social, political, and economic well-being of the citizens. Because of its significance, any loss, whether total or partial, or compromise, might result in significant human casualties, have a negative effect on the economy, have other negative social repercussions for the community, or give the national government immediate concern. These support services have contributed to the never-ending demand for instant access to information and communications technology as well as the desire among customers to receive extremely fast and reliable service from mobile switching centers or data centers. According to ASHRAE 2008 environmental guidelines, which states that data centers should be maintained between 18°C and 22°C, while cooling system requirements range from 30% to 40% of the total installed energy infrastructure in every mobile switching center or data center (Liquori, 2022; Yasar et al., 2022). As a result, very strict maintenance programs must be adhered to in order to ensure optimal cooling (McMorrow, 2019). This is because of the effects of temperature and humidity on IT equipment reliability and the corresponding impact on business supply chain - reputational damage and impact on customer experience. In order to assure end-user happiness, which depends on the accessibility of the data center services, the data center's reliability is crucial. To do this, the medium and low voltage distribution network of the data center is carefully assessed/evaluated in order to examine and comprehend the behavior of the system, including MTTF, MTTR, MTBF, system reliability, and failure rate during normal operation and a system fault, in order to determine the fault(s) in the system, the parameters that are responsible for the fault, and why they are not functioning properly. This research considers the reliability of the raw power which comprises the utility supply, the AVR, the automatic transfer switch, the standby power (diesel generators), the conditioned power (the UPS power supply) and distribution topology. It also considers the installed Heating and Ventilating Air Conditioners (HVACs) installed in each of the prefab rooms to achieve optimum and sustainable cooling. The major problem has remained grid power fluctuation and instability which cause reduced Cooling Capacity due to frequent restarts and reduced MTBF of the cooling HVACs, premature IT equipment failure due to inefficient heat removal from the prefab rooms. These cause increased operational cost because of the prolonged use of standby power supply during grid power fluctuations – equipment damage, tear and wear on DG and associated diesel cost. The data center reliability is evaluated using the results from the study which is developed into a model to ensure that the topology adopted is most suitable to achieve the needed redundancy and maintenance programs that will give the level of reliability needed to ensure improved power and cooling availability in the mobile switching center/data center. According to Yasar et al., in the data center industry, equipment redundancy is widely utilized to achieve high system availability, often required to be in the range of 99.999% (five nines) while designs can now be certified as simultaneously "concurrently maintainable" and "fault-tolerant." These designs have not only eliminated single points of failure, but remain fault-tolerant even when equipment and systems have been isolated for maintenance and repairs (Yasar et al., 2022).

Literature Review

The "Telecommunications Infrastructure Standard for Data Centers" standard, released by the American National Standards Institute and the Telecommunications Industry Association in 2005, outlines four tiers of data center design and implementation criteria (Loshin & Lutkevich, 2021; Yasar et al., 2022; Borgini, 2020). Available resources, data center capabilities, or uptime assurances can be used to distinguish between tiers. The following is how the Uptime Institute defines data center tiers:

Tier I. These are the most fundamental data centers and include a UPS. Tier I data centers should provide at least 99.671% uptime but not redundant systems (Yasar et al., 2022).

Tier II. These data centers ensure at least 99.741% uptime and have redundant systems for power, cooling, and other components (Yasar et al., 2022).

Tier III. These data centers offer 99.982% uptime assurance, full redundancy, 72 hours of outage protection, partial fault tolerance, and (Yasar et al., 2022).

Tier IV. These data centers guarantee 96 hours of outage protection, full fault tolerance, and no more than 26.3 minutes of downtime annually. They also promise 99.995% uptime (Yasar et al., 2022).

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Cooling Infrastructure

Traditional refrigerant-based HVAC (Heating and Ventilating Air Conditioner) units connected to condensing units outside the building make up the cooling infrastructure of a data center. These systems, according to Kriech (2020) and Pearl (2015), are in charge of circulating air throughout the data center, often by means of sizable fans that travel through the plenum to the air vents.

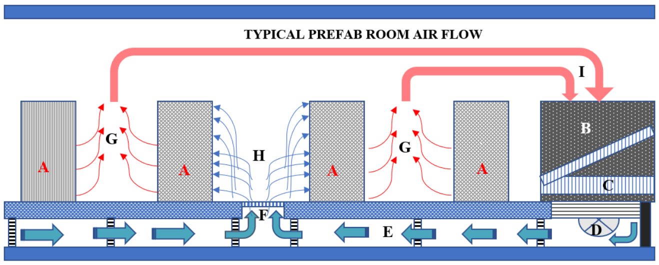

Figure 1: Air Flow inside Prefab Room

Figure 1 is a schematic to show the normal air flow inside a prefab room. From the schematic, "**A**" represents the racks housing the servers and the IT equipment, "**B**" represents the HVAC, "**C**" represents the heat exchanger, while "**D**" represents the blower that forces the cool air through the plenum (raised floor). "**E**" is the plenum with arrows pointing to the direction of the cool air and "**F**" is the vent through which the cool air leaves the plenum. "**G**" and "**H**" represent the hot and cold aisle while "**I**" is the hot air return to the HVAC for another heat exchange cycle. Maintaining a constant temperature inside the data center by using a steady and specified data center setpoint temperature is still the standard cooling philosophy. The HVAC evaporators cool the air as it circulates through the floor plenum. When this air enters the floor vents, server fans direct it through the servers, where heated air rises to the return plenum. Data centers have lately shifted to a cost-effective cooling alternative based on adiabatic cooling. According to the underlying theory, data centers can be cooled by outside air for the most of the year. However, during the short hours when the outside air gets warmer, evaporative cooling is employed to cool the incoming air through the air flow path. This approach still circulates air inside the data center using fans and air handlers (Pearl, 2015; Kriech, 2020). Efficiency of the cooling infrastructure affects the amount of electricity used by the cooling equipment and directly affects the data center's PUE (Power Usage Effectiveness). PUE is defined as the ratio between power consumed by the data center to the power consumed by the IT infrastructure alone. Since each server component has a specified operating temperature range, cooling also directly affects how well those components' function. According to Shrestha, (2016), the component's behavior is not guaranteed outside of the specification because it could possibly malfunction or shut down, which would make the server unavailable.

Figure 2: A – 35KW Hvacs, B – Plenum Air Forced Extractor Fan on Raised Floor

Figure 2 shows the picture of a 35KW HVAC, and extractor fans which are used to force cool air circulation under the plenum through the vents usually targeted and positioned around the cold isles. One of the most common failing parts has been discovered as a hard drive, and researchers have measured how temperature affects HDD failures in a big data center facility (Shrestha, 2016; Pearl, 2015; Kriech, 2020).

While designing data center cooling systems receives a lot of attention, the majority of that attention is focused on increasing utility power operations' efficiency and dependability. The lack of straightforward tools for data center designers and operators to forecast cooling performance under such settings contributes to the lack of attention given to emergency operating conditions (Pearl, 2015; Churazova, 2021).

Power Infrastructure

Elkadeem et al. (2017) introduced a general approach for the affordable implementation and evaluation of advanced distribution automation systems (ADAS), capable of fault localization, isolation, and service restoration (FLISR). He (2002) presented the modeling and evaluating the impact of automation, protection, and control on the reliability of power distribution systems. He also confirmed from his analysis that customer failure statistics have shown that the distribution systems are the major cause of customers' inability to get a power supply. According to the author, increasing the level of automation and control must be taken into account in order to increase reliability. Similarly, Reddy & Meikandasivam (2018) claimed that the only way to guarantee the longevity of the power supply grid was to make it an intelligent, well-established, automated, and, most importantly, environmentally friendly energized network.

The research by Sahebkar Farkhani et al. (2020), examined the traditional coordination of the protection system, which is based on the time delays between relays as the primary and backup protection system, and offered solutions for the microgrid protection problems. According to Elkadeem et al. (2017), the automated network with proposed ADAS has a significant benefit through a reduction in reliability indices (SAIDI and EENS exhibit a significant reduction by 34% and 32%, respectively). The authors suggested changing the protective relay settings and the optimal placement of reclosers. Additionally, it has been shown to have outstanding advantages in terms of improving consumer quality of experience/satisfaction and decreasing fines from industry regulators (Elkadeem et al., 2017). He (2002) confirmed from his analysis that using the developed models and techniques, the overall reliability benefit can be improved as the reliability of the control system increases, but the scope of this improvement is only limited to the information and communication technology used for the feeder automation (He, 2002). The author suggested that the goal of his work, which was to create analytical models, techniques, and computer programs, could be used to quantify the reliability improvement related to automation and control. He (2002) also included the impact of automation and control in the distribution systems' reliability assessment. The author insisted that FLISR is one of the most advantageous and appealing uses of ADAS for reliability improvement and self-healing. Adaptive protection and intelligent protection, which operate on the basis of communication with modern digital protective relays employing PMU and IDM, should be included in protection systems for power distribution networks and microgrids in the future. This will improve data centers' access to power (Sahebkar Farkhani et al., 2020).

Methodology

To achieve the aim of this research work, the first work done was to carry out a detailed characterization of the network under study. This was done to determine the behaviour of the key performance parameters MTTF, MTTR, MTBF, system reliability and failure rate. This will also help us monitor the temperature rise in the prefab rooms during loss of power or cooling failure to know how quickly cooling interventions should be done to avert abnormal temperature rise. Details of the work done are presented and the model of the characterized network, developed and simulated. Having characterized and developed a model of the network under study, the next work done was to develop a controller that is able to predict when there is likelihood of system failure and to isolate the fault section and restore power to affected units. An algorithm to make this controller adaptive was developed. Details of all the work done to achieve the above are shown below. Finally, the model was integrated into the model of the network and overall system was simulated to evaluate its performance and hence the percentage improvement.

Block Diagram Model of Measurement Setup

The data for this work was obtained from the Human Machine Interface of the Scada panel inside MTN Enugu Switch Energy Center which is powered on a 24Vdc supply from a DC-DC converter and the 24Vdc supply from the diesel generator (DG) battery. The DC-DC converter is connected on the UPS circuit to ensure data stored on the HMI is always retained. The HMI by default can retain data for 6months at which stage it purges itself of data on first in first out basis (FIFO). The HMI has input terminals for the power sources, output terminals for the distribution breakers feeding the Switch prefab rooms (Prefab 01 – Prefab06), feedback control input, alarms, and status indication lamps.

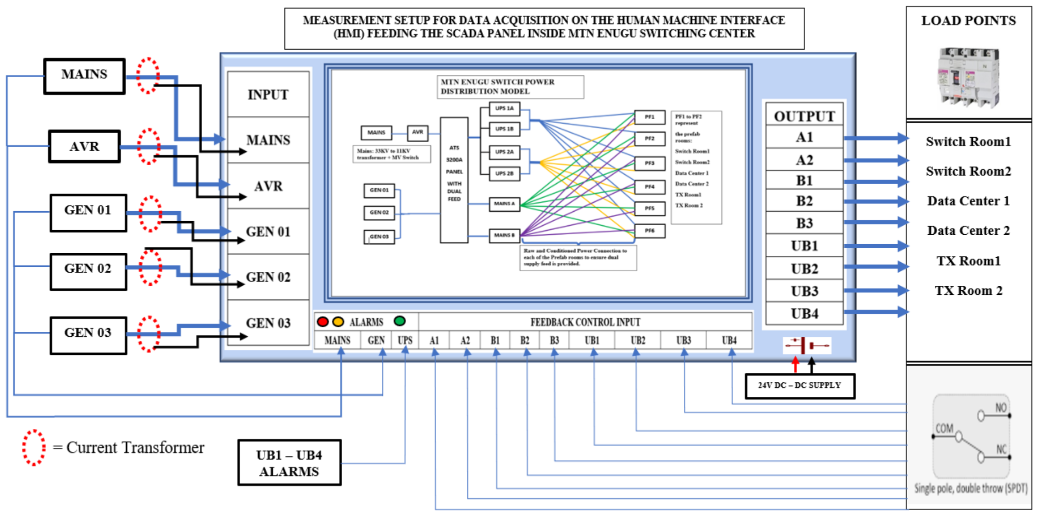

Figure 3: Block Diagram of Measurement Setup

The power source input terminals on the HMI have the AC input lines from the transformer, AVR and standby generators. The voltage levels are monitored from the LV distribution panel through the AC input lines while the current monitoring is achieved through the CT (this is coloured red). The CTs are 5A/3200A which is meant to capture the full load current of each of the sources. The distribution breakers feeding the prefab rooms received their close or open command from the HMI output terminals and provide feedback on command execution through normally open (NO) or normally closed (NC) contact in the LV distribution panel to the feedback control input terminals. The Alarm input terminals are wired to ensure supervisory functions on all the power sources, distribution breakers and UPS and report through the alarm indication lamp status. The voltage level per phase, current per phase, power per phase and alarms for each of the distribution feeder breakers can be read off from the HMI. The HMI can be queried to provide data on each breaker failure time and failure clear time and can support 6 months of data enquiry. For this test, data was collected for a one-year period to accommodate and monitor the impact of the various seasons on the availability/service hours of the breakers. The measurement setup is shown above in figure 3. The experiments were carried out jointly by myself, the field technician in the Switch center and his supervisor. Care was taken to ensure the data we obtained was relevant to the study.

The HMI reports were calibrated to suit the measurement template –the search criteria were expanded from weekly to see daily performance reports and on the daily, we also expanded to see the hours of the day the breaker failure occurred. The weekly service hours availability of the breakers over 8760hrs of the year was reduced down to weekly figures represented in percentage to show the service availability of each breaker in 168hrs of the week. The raw data for the weekly service availability report for the switch passive infrastructure – Power and Cooling is shown in Appendix A1.

MTN Enugu mobile switching center is located at Zoo estate, normally referred to as Ekulu East estate GRA. In this work, we shall characterize the power infrastructure and distribution network. The power distribution network comprises an overhead 33kV line from the Thinkers Corner injection substation. The metering infrastructure – the

CVTs and the CT are located at the HT pole and this supply feeds a MV switch gear which provides protection through it's relays on the HV side.

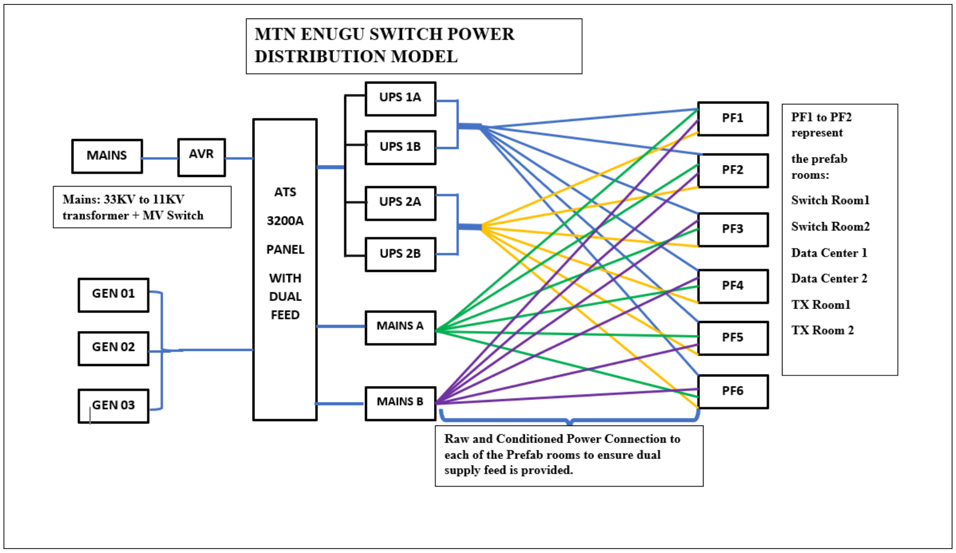

Figure 4: Power Distribution Flow Diagram

At the load points presented in Figure 4, a 1.5MVA transformer further reduces the voltage on the MV panel from 33kV 11kV which is fed to another 1.5MVA transformer which reduces the voltage further to 415V to provide the last-kilometer connection through 415V feeders on the LV panel to the AVR and 500kVa power factor correction equipment. The output of the AVR feeds an automatic transfer switch which is capable of selecting from three standby energy sources – 3 X 1.5MVA generators to provide the required redundancy of 3N + 1 necessary to guarantee stable supply. The 3200A ATS panel is properly dimensioned to provide dual power supply feed for all the power distribution boards for the six prefab rooms and all connected equipment is installed with dual power sources so that in the event of a supply input failure, the second supply input is able to provide enough power to support the switching center energy requirement. Part of the steady state strategy is to ensure that the load at any time on each power source does not exceed 65% utilization so that recovery from failure is seamless because of the battery energy storage systems that need to recharge and also because the compressors in the HVACs will run a much longer period to overcome the heat load from the equipment. In the Switching center, there are two data centers for the servers and routers, two equipment rooms for the BSCs and RNCs and two transmission rooms.

Similarly, temperature measurements were carried out using Fluke TiS40 thermal imager which helped to monitor the heat profile of the prefab rooms during the Mains failure simulation while Fluke 971 Temperature Humidity Meter helped to monitor if we were maintaining optimal comfort levels and good indoor air quality in the prefab rooms during the experiment.

Below are the average readings obtained for each of the prefab rooms during a power changeover.

Table 1: Prefab Temperature Rise Vs. Time

Prefab Rooms	Time for temp rise from 22°C to 25°C (Mins)	Time for temp rise from 26°C to 30°C (Mins)	Time for temp rise from 31°C to 45°C (Mins)	Time for temp rise from 45°C to 60°C (Mins)
Prefab 01	2.8	7.2	12	17
Prefab 02	2.6	6.9	13	18
Prefab 03	3.0	7.3	12	17
Prefab 04	3.0	7.2	13	17
Prefab 05	2.8	7.1	14	18
Prefab 06	2.7	7.3	13	18

During a power changeover from mains supply to DG 1, DG2 or DG3, there is temporary power loss to the cooling equipment (HVACs). The generator starts after about one minute and provides power to the HVACs.

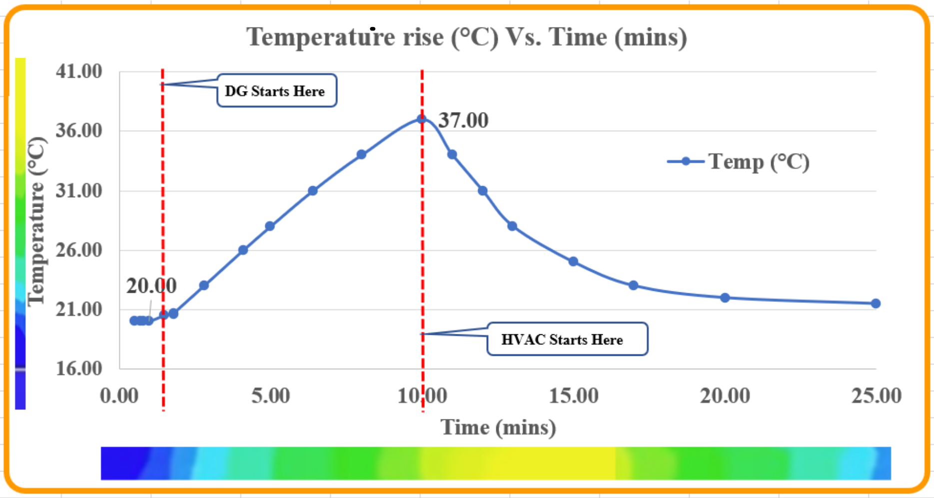

Figure 5: Temperature Time Graph for A Normal Power Changeover

At this point, only the cool air trapped under the plenum is pushed through the vents and circulated which causes the room temperature to drop slightly and then begins to rise when the cool trapped air is overwhelmed by the shelter heat load since there is no heat exchange.

After about 10mins, the HVACs start to cool- and at this point, the temperature begins to drop until it hits the room temperature set point at which point it begins to regulate as seen on the graph. This is presented in Table 1 and Figure 5. We can also see from the graph that this cycle takes a minimum of 25 mins to recover and sustain the cooling capacity after an outage.

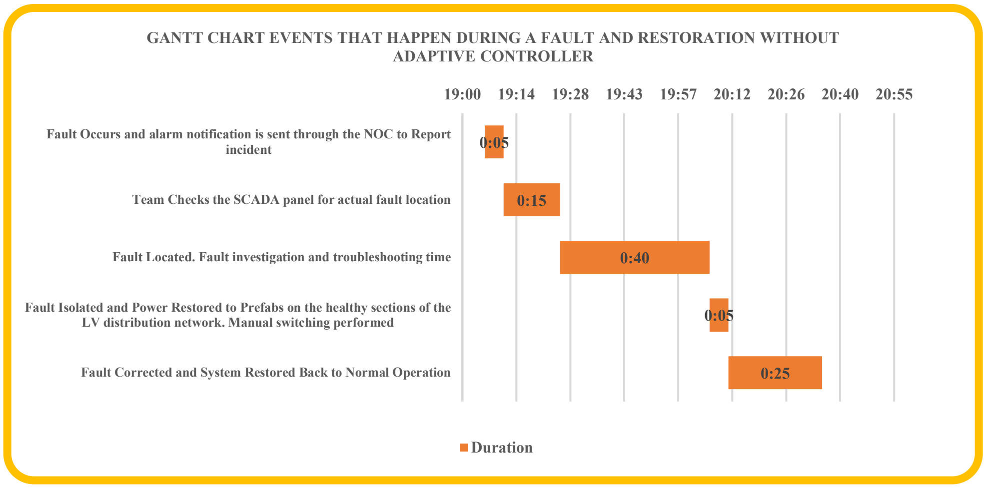

Figure 6: Power Outage Callout Event Log Without the Adaptive Controller

For prolonged outages due to distribution fault, it was observed from the operator's call-out log presented in a Gantt chart in Figure 6 that fault location, isolation and service restoration are done manually leading to high MTTR on fault resolution. It is evident from the graph that it took 5minute to properly document the fault incident and notify the resident technicians in the switch yard, 15 minutes for the team to confirm the actual fault location on the SCADA panel, and 40 minutes to investigate and troubleshoot the fault, another 5minutes to perform manual fault isolation successfully. Another 25 minutes was used to correct fault and fully restore system to normal operation. This is a total of 65 to 90 minutes of fault intervention despite the anticipated rapid rising room temperature.

Simulink Models of Power Source

The first work done in this section was to model the power source that will power the entire model. This was modelled in Simulink using three-phase voltage sources, three phase transformer three-phase V-I measurement block, three phase breaker, power measurement block and the RMS block from Simulink library. Figure 7 and 8 shows the various sections that make up the model of the power source which is referred to in MTN Enugu Switch as the Energy Center and the V-I waveform. The various components used were parameterized to ensure the output voltage, frequency stay within the healthy limits that will allow the models work efficiently. The makeup of the various sections is described below:

Section A: The power source and comprises the 33KV power source, a breaker and a 1.5MVA transformer. Section B, C and E displays the total values of the voltage and current at the input, Zones A and B. Section D has a relay which controls the main supply breakers – for zones A & B.

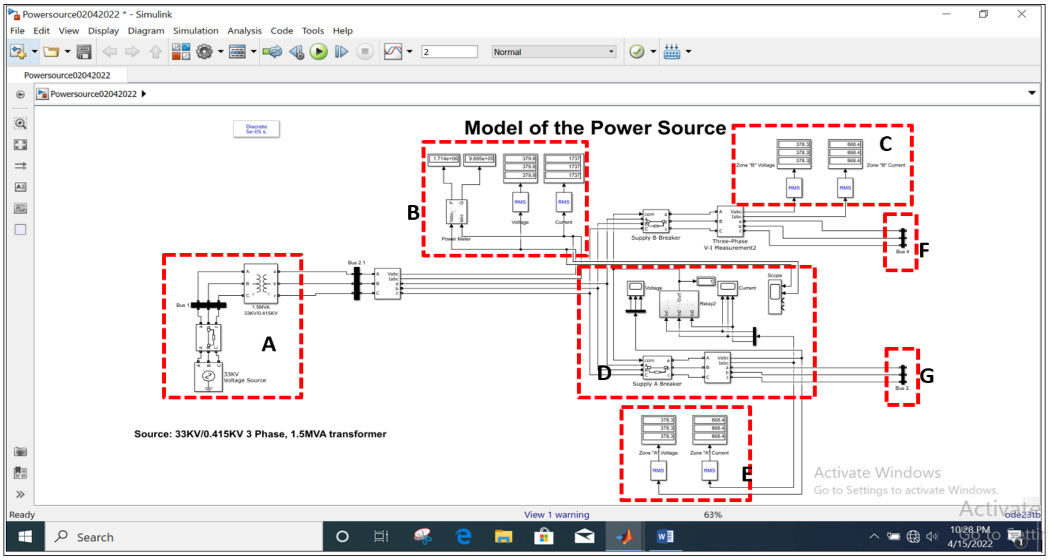

Figure 7: Model the Power Source

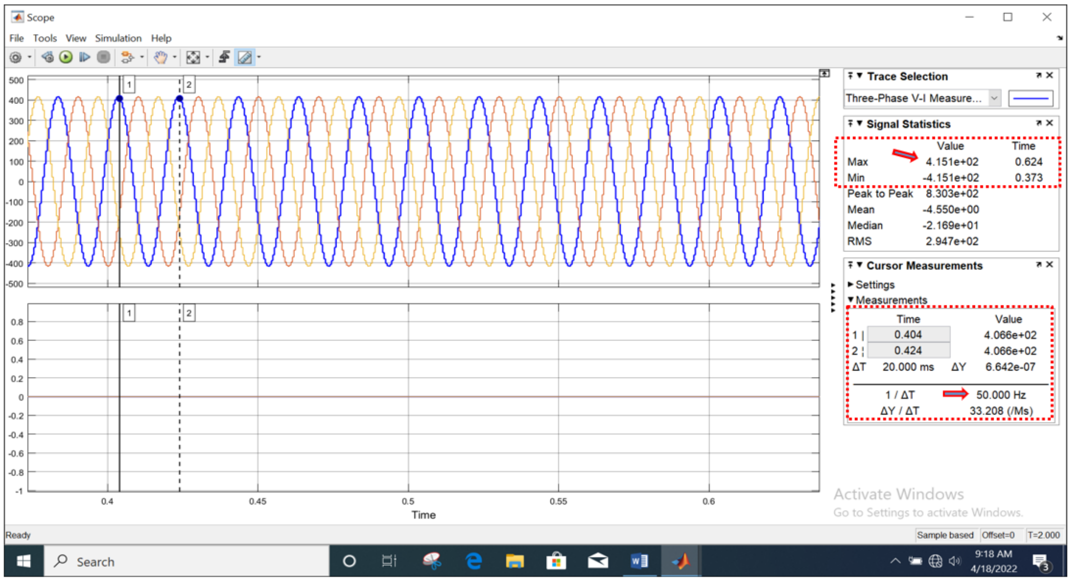

Figure 8: Wave Form of Power Source

Section F and G provide the bus connection points to the LV distribution panel that feeds all the prefab rooms in MTN Enugu Switch. The proposed controller for the LV distribution network comprises the protection relay which comprises current sense relay, temperature controller, cooling intervention controller and the controller logic. These were modelled in Simulink as shown in Figure 8, 11, 14 and 15.

Protection Relay

The Protection Relay subsystem comprises the current sense relay subsystem, State flow chart subsystem, three-phase breaker block, three-phase V-I measurement block, RMS block and display block and is all contained in the Sim power system library in Simulink. The complete model is presented in Figure 9

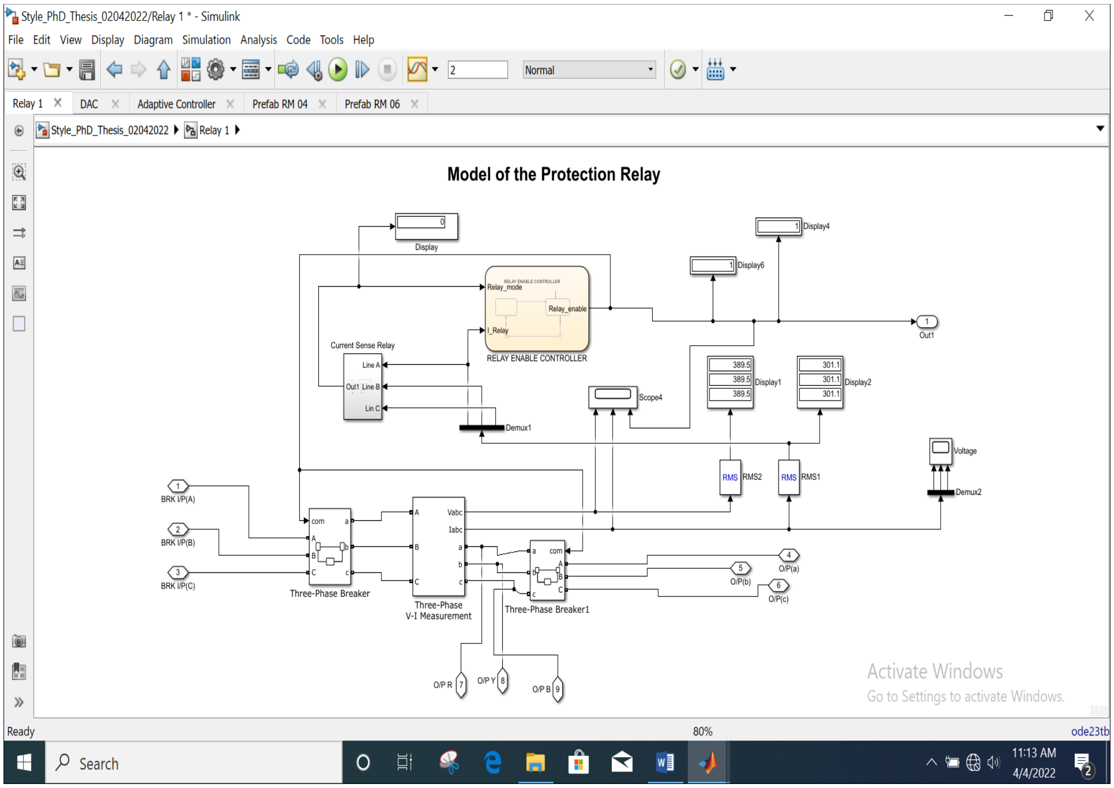

Figure 9: Model of the Protection Relay

The three-phase V-I Measurement block monitors the line voltages and current through the Vabc and Iabc terminals. Vabc and Iabc display the voltage and Current levels of the load on the display blocks.

To achieve a precise overcurrent protection from line over-load or short circuit current, Iabc output of the three-phase V-I measurement block through an RMS block, is fed to the current sense relay so that the current readings on each of the lines are monitored. A reference current sense input, I, Relay on the State flow chart is also fed from one of the input lines from the current sense relay input. The State flow chart provides a secondary current protection which is activated by the I Relay input also monitors the current level at its input and sustains its output at logic 1 as long as the current level is within the set threshold. This feeds the State flow Relay mode input. The fault conditions are defined as logical expressions such that whenever the sense input, sees that the current exceeds the preset value, the system immediately disables the breaker enable input which in effect isolates the breaker. The breaker block was used to provide a safe connection of the supply to each of the prefab rooms

Vol. 3, No. 6 | 2022 | pp. 1-26 | *DOI: https://doi.org/10.5281/zenodo.7413430*

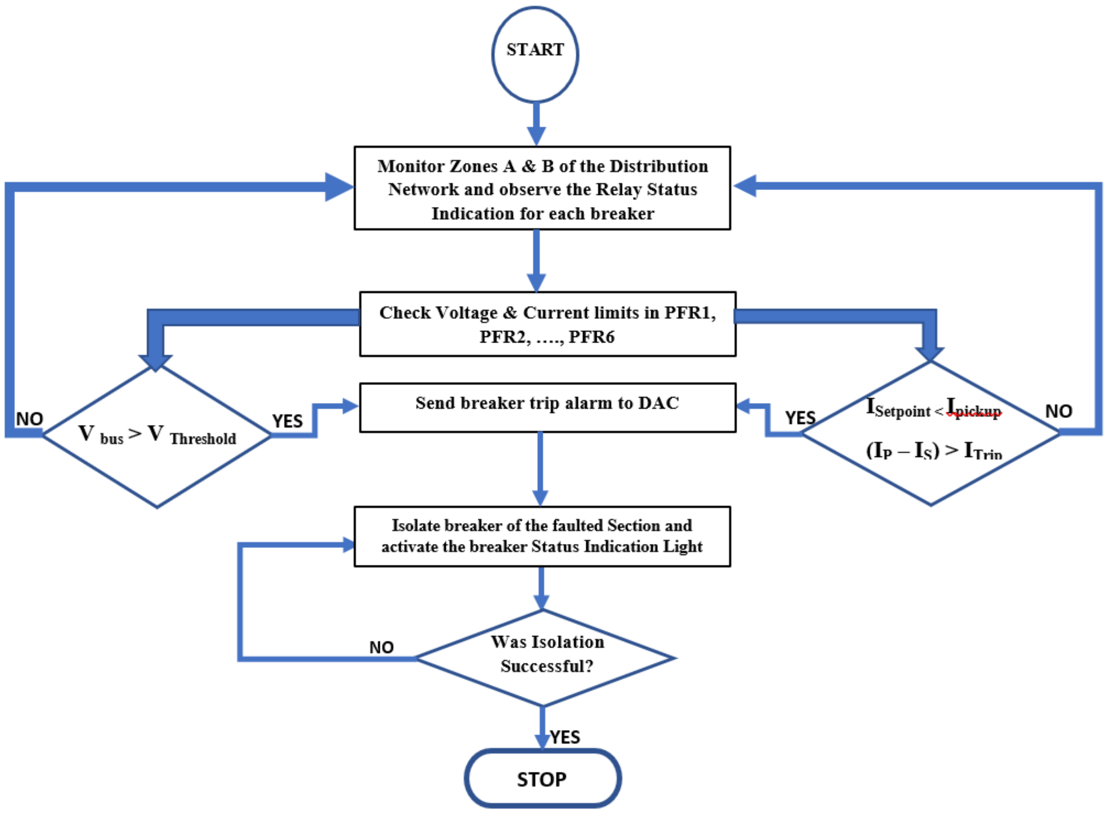

Figure 10: Flowchart for the Operation of the Protection Relay

The steps below describe the processes and procedure of operation of the Protection relay as illustrated in the flowchart of Figure 10;

Step 1: The first step in the procedure is the monitoring of the LV power distribution feed to the Prefab rooms whose supply feed is categorized into zones A & B. The relays have indication lamps that provide information on its operational status.

Step 2: Monitoring continues with checks on the voltage and current levels in the prefab rooms to know if they are within the defined limits.

Step 3: When the bus voltage or the pickup current are outside the safe operation limits and exceeds the pre-set values on the protection relay circuit the controller will use its decision logic to flag the anomaly.

Step 4: The distribution automation controller (DAC) receives the flag and isolates the fault sections of the distribution network. At the same time, it activates the breaker status indication light to indicate that there is a fault on the relay and that the relay isolation was successful.

Temperature Controller

The temperature monitoring and management for each of the prefab rooms were modelled using the State flow chart presented in Figure 11 and shows the state transition diagrams and conditions that must be satisfied for the controller to be in the normal state or fault state.

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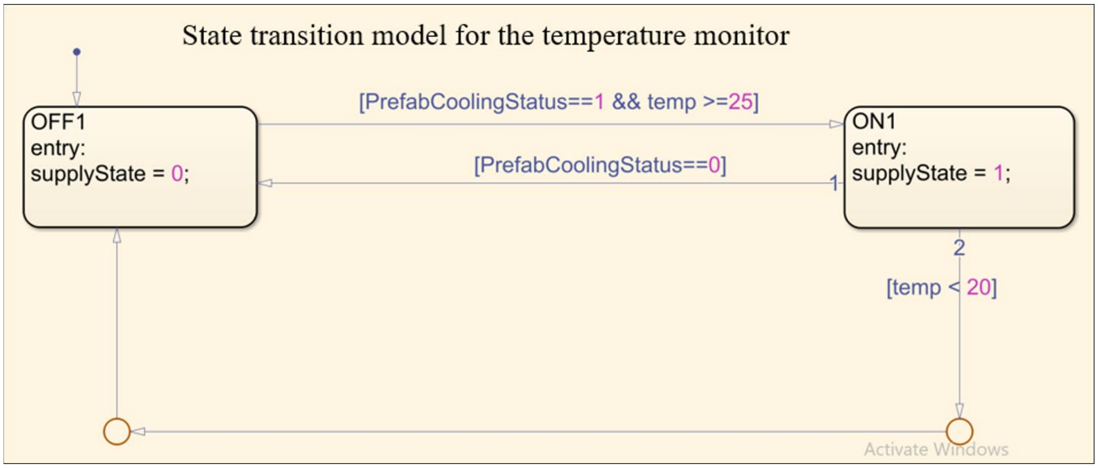

Figure 11: State Transition Model for the Temperature Monitor in the Adaptive Controller

This supervisory unit was modelled to anticipate abrupt changes to the control loop and consists of state transition diagrams that consists of two states – ON and OFF. Each state represents when different control rules are in use, with the ON State exited when the temperature exceeds the set point in the rules. The prefab room temperature monitoring and heat exchange control presented in Figure 12 was implemented using a temperature scale whose slider-pointer slides across a given range of temperature. The set point trigger activates at > 25°C which was set according to ASHRAE's guideline for optimum cooling of the IT nodes and BESS. Figure 12 and 13 presents the temperature monitor and how it is connected to the DAC. During a fault, the prefab temperature input picks the rapid rise in temperature, while the cooling status monitors the supply to the cooling. When a distribution fault occurs, and room temperature exceeds the set point on the controller, the fault state rules on the State flow chart will close the standby HVAC breaker to connect the standby cooling to the supply from the healthy part of the LV distribution or an alternative energy source.

The standby units are expected to continue to work until the temperature drops below 22°C after fault resolution.

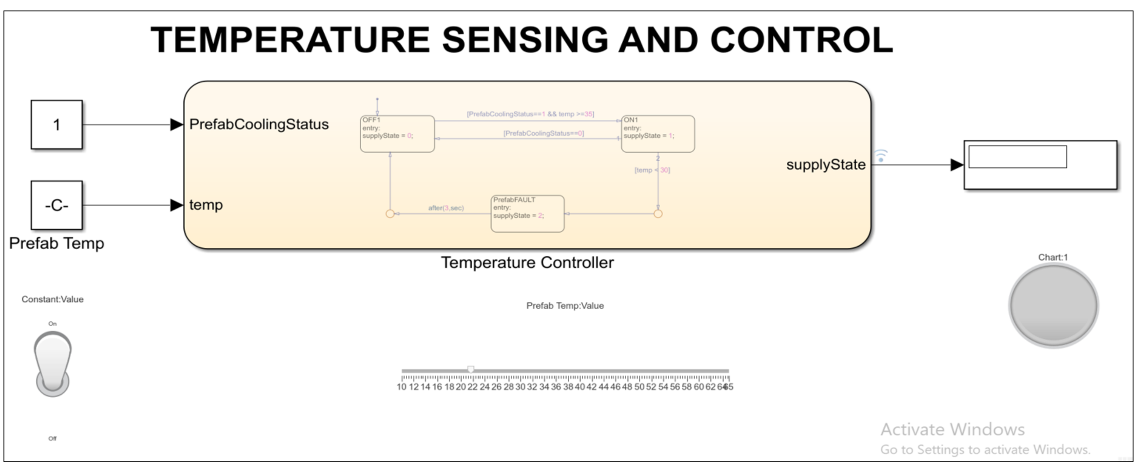

Figure 12: Model of the Temperature Monitor in the Adaptive Controller

Vol. 3, No. 6 | 2022 | pp. 1-26 | *DOI: https://doi.org/10.5281/zenodo.7413430*

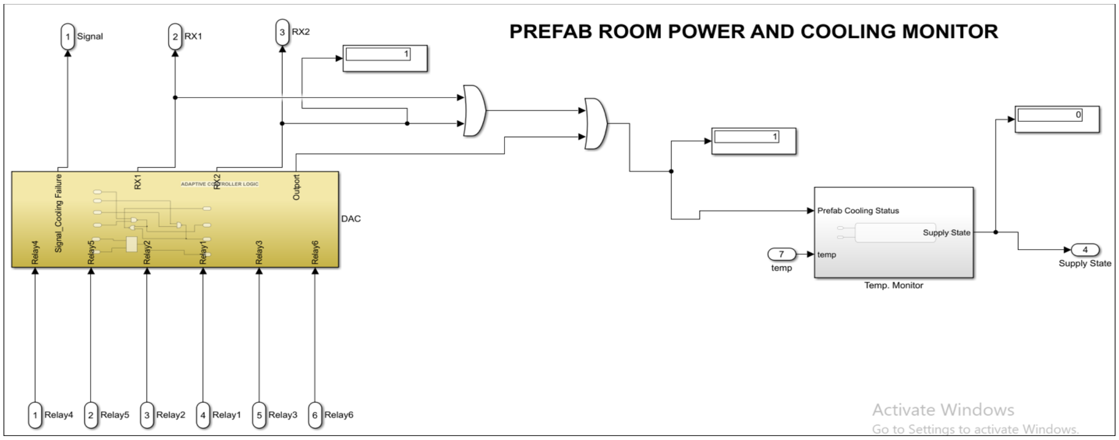

Figure 13: Prefab Room and Cooling Monitor

Figure 14 shows the sequence of actions involved in the operation of the Temperature Controller. The step-by-step sequence of actions of the temperature sensing and control flowchart is described below;

Step 1: The temperature sense and control, monitor the supply breaker voltage – normal supply and alternative supply in each of the prefab rooms.

Step 2: Checks for loss of power or cooling in the prefab room.

Step 3: Check and confirm if prefab temperature is below the 25ºC setpoint. If above the setpoint, the fault state rules on the State flow chart will activate the cooling intervention controller to supply the standby HVACs from the healthy part of the LV distribution network.

Step 4: Checks to confirm the standby cooling is ON and continues to sustain prefab cooling through the cooling intervention controller until the relay fault is resolved and cooling sustainably restored.

Step 5: Check and confirm if prefab temperature is less than 23ºC. If yes, disconnect the standby cooling unit so that normal operation continues.

This is when the adaptive controller closes the breaker for the alternative power source to supply the prefab standby cooling units. The standby units will continue to work until the temperature drops below 22ºC after fault resolution.

Vol. 3, No. 6 | 2022 | pp. 1-26 | *DOI: https://doi.org/10.5281/zenodo.7413430*

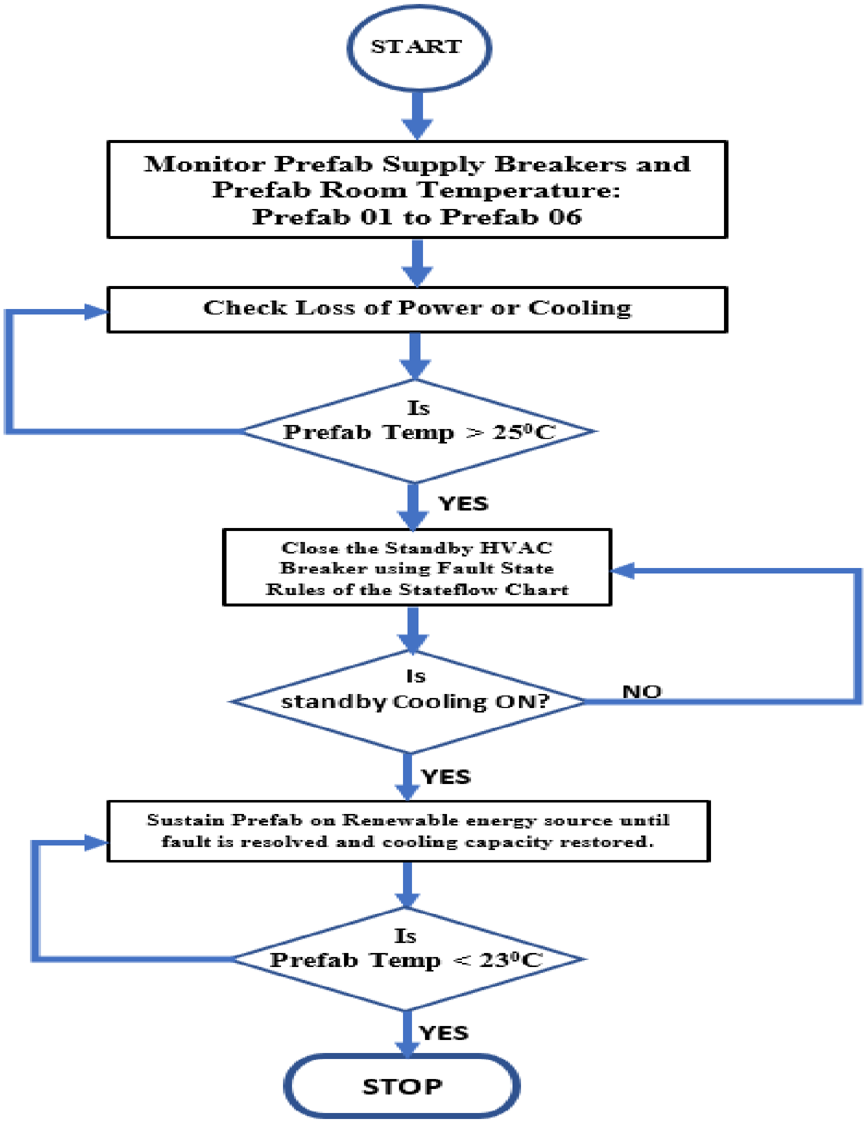

Figure 14: Temperature Sensing and Control Flowchart

Cooling Intervention Controller

The cooling intervention controller which is responsible to restore power to standby HVACs in prefab rooms and comprised of the voltage sensing relay, three-phase breakers with external control input, logic gates, display block for visualization of the control signals, the prefab load and the standby HVAC load.

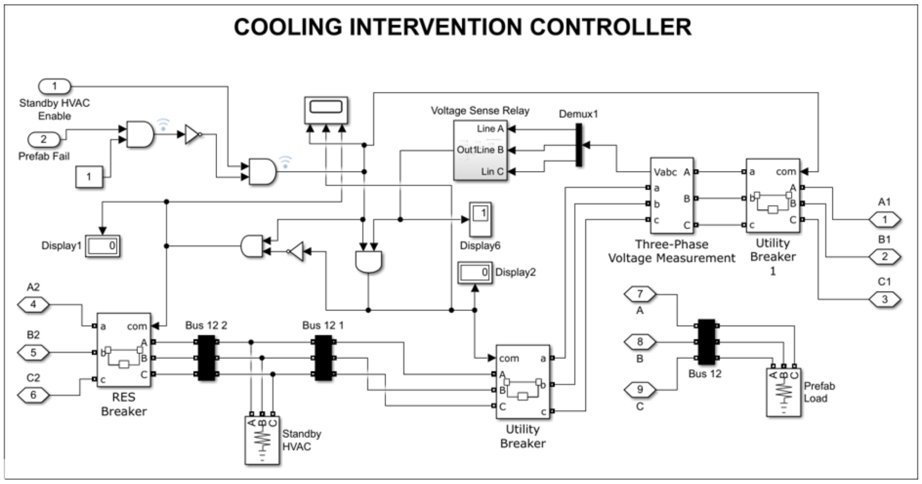

Figure 15: Cooling Intervention Controller

The initial states of these inputs signals during normal operation are: Standby HVAC (SHE) = 0 and Prefab Fail (PF) = 1, and during cooling failure, SHE = 1, and immediately the temperature increases above set point, PF = 0. After a successful fault isolation, the voltage sensing relay presented in Figure 15 checks for availability of power source from the healthy part of LV distribution network by monitoring the voltage levels. If voltage levels are healthy, it connects the standby HVACs restore cooling

Controller Logic

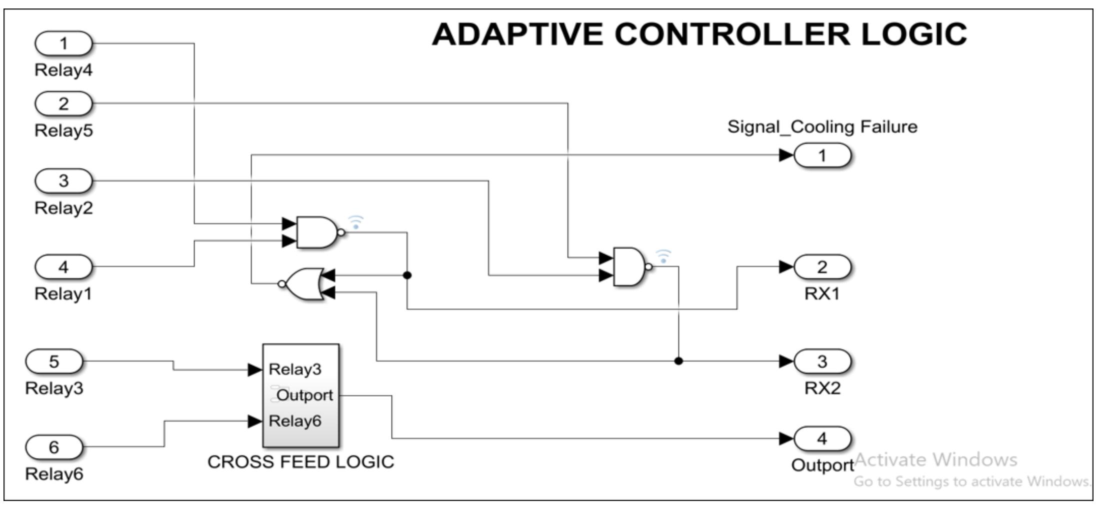

Figure 16: Model of the Controller Logic

The model of the controller logic is presented in Figure 16 was modelled to use logic operators for its monitoring and control functions. It receives the output of the protection relays, R1 to R6 as its input and combines it to make precise switching decisions. Relay 1 (R1) and Relay (2) combine on a NAND gate to give an output that enables cross-feed breaker RX1 to close whenever it has logic 1. Similarly, Relay 5(R5) and Relay 2(R2) combine to give an output that enables the second cross-feed breaker (RX2) to either close or open. RX1 and RX2 breakers will only close when the breaker enable input is on logic 1.

Relay 3 (R3) and Relay 6(R6) combine through an OR gate to give an output through the output port of the controller. The cross-feed breakers RX1 and RX2 further combine through a NAND gate to enable prefab room temperature monitoring. These logic operators were implemented to enable the adaptive controller to perform FLISR.

Intelligent Algorithm for the Adaptive Controller

An intelligent algorithm to make the controller adaptive was developed through a logical step-by-step analysis of the sequence of actions involved in each of the different models that make up the adaptive controller. These sequences of actions were developed into the flowchart presented in Figure 17 to illustrate the algorithm for the controller visually. The algorithm provides a procedure for the safe isolation of the fault section of the switching center distribution and how to monitor the temperature of the affected prefab room to ensure that the room temperature does not rise above 18 to 25°C recommended by AHRAE for optimum performance of the IT nodes and BESS. Below steps describe the procedures in the execution of the algorithm. The C – Code for the Adaptive controller is shown in Appendix A4.

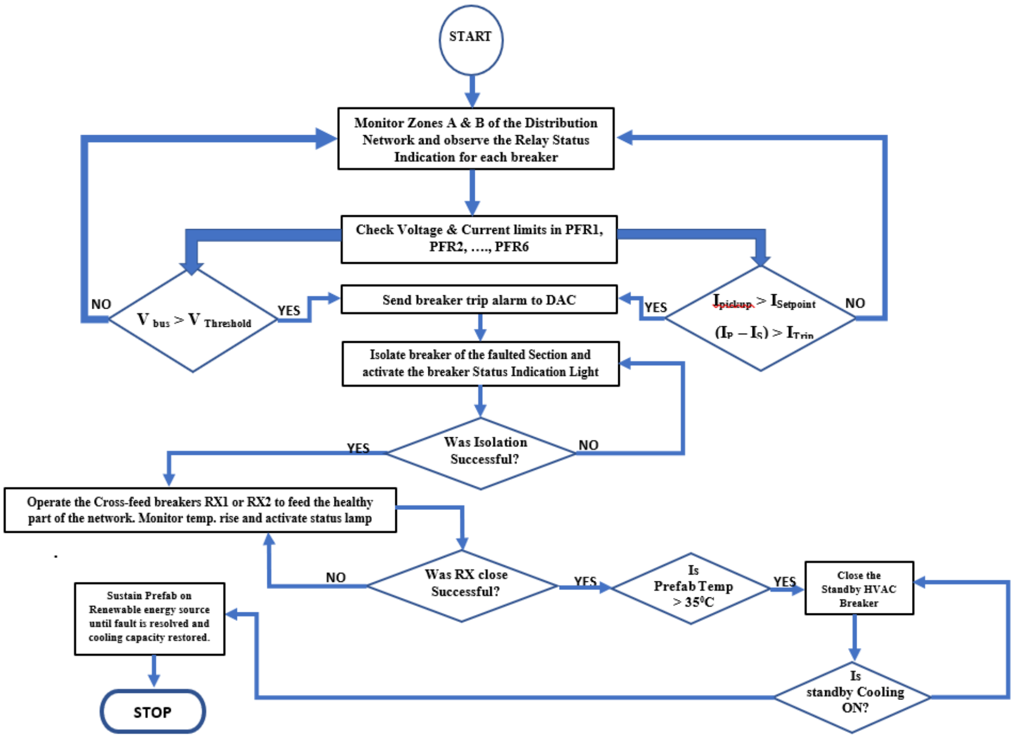

Figure 17: Flowchart for the Adaptive Controller

Step 1: The first step in the procedure is the monitoring of the LV power distribution feed to the Prefab rooms whose supply feed is categorized into zones A & B through the protection relays R1 to R6. The relays have indication lamps that provide information on the operational status of the relays. Monitoring continues until the values for voltage and current exceed the preset values set on the current sensing relay circuit.

Step 2: The monitoring circuit also checks the voltage and current levels in the prefab rooms. If the voltage and current levels are within the defined limits, the system continues to monitor. However, if the current or voltage levels are outside the safe operation limits of the controller, the controller will use its decision logic to flag the anomaly.

Step 3 & 4: The controller will identify the fault location and send out breaker open commands to properly isolate the fault section. After this is done, the controller status indication lamps turn from RED to GREEN. The controller through its crossfeed breakers RX1 & RX2 restores supply to a healthy part of distribution affected by the relay trip.

Step 5&6: The controller checks if prefab isolation was successful and continues to monitor the temperature of the affected prefab. As soon as the temperature increases above 25°C, it sends the breaker close command to supply the standby cooling unit through the healthy part of the distribution.

Vol. 3, No. 6 | 2022 | pp. 1-26 | *DOI: https://doi.org/10.5281/zenodo.7413430*

Step 7: The controller continues to monitor until fault restoration is completed and room temperature is restored to normal operating status.

Integration of All the Developed Models of the Controller

The complete model for the Mitigation of the Impact of Cooling System Failure in a Mobile Switching Center an Adaptive Controller was developed by interconnecting the various subsystem described in section 3. These include - protection relay model for each of the switching center Prefabs, the temperature controller, the cooling intervention controller and the controller logic. The complete model gives an adaptive controller capable of localizing the fault section of the switching center with an indication lamp which turns from RED to Green, isolates the fault section of the LV power distribution and restores power to the healthy part of the distribution. While doing this, it also monitors the temperature of the affected prefab and puts up a temperature alarm warning indicator (from Green to Amber) and also provides power supply to the standby HVACs from the healthy part of the LV distribution to restore cooling before the field team are able to resolve the fault. The model picture is shown in Figure 18.

Adaptive Controller

The adaptive controller presented in Figure 18 makes use of logic operators for its monitoring and control functions. It receives the output of the protection relays, R1 to R6 as its input and combines it to make precise switching decisions. Relay 1 (R1) and Relay (2) combine on a NAND gate to give an output that enables cross-feed breaker RX1 to close whenever it has logic 1. Similarly, Relay 5(R5) and Relay 2(R2) combines to give an output that enables the second cross-feed breaker (RX2) to either close or open. RX1 and RX2 breakers will on close when the breaker enable input is on logic 1. Relay 3 (R3) and Relay 6(R6) combine through an OR gate to give an output through the output port of the adaptive controller. The cross-feed breakers RX1 and RX2 further combines through a NAND gate to enable prefab room temperature monitoring. The output of RX1 and RX2 combines through an OR gate to combine with the output R3 and R6. These logic operators were implemented to enable the adaptive controller perform FLISR.

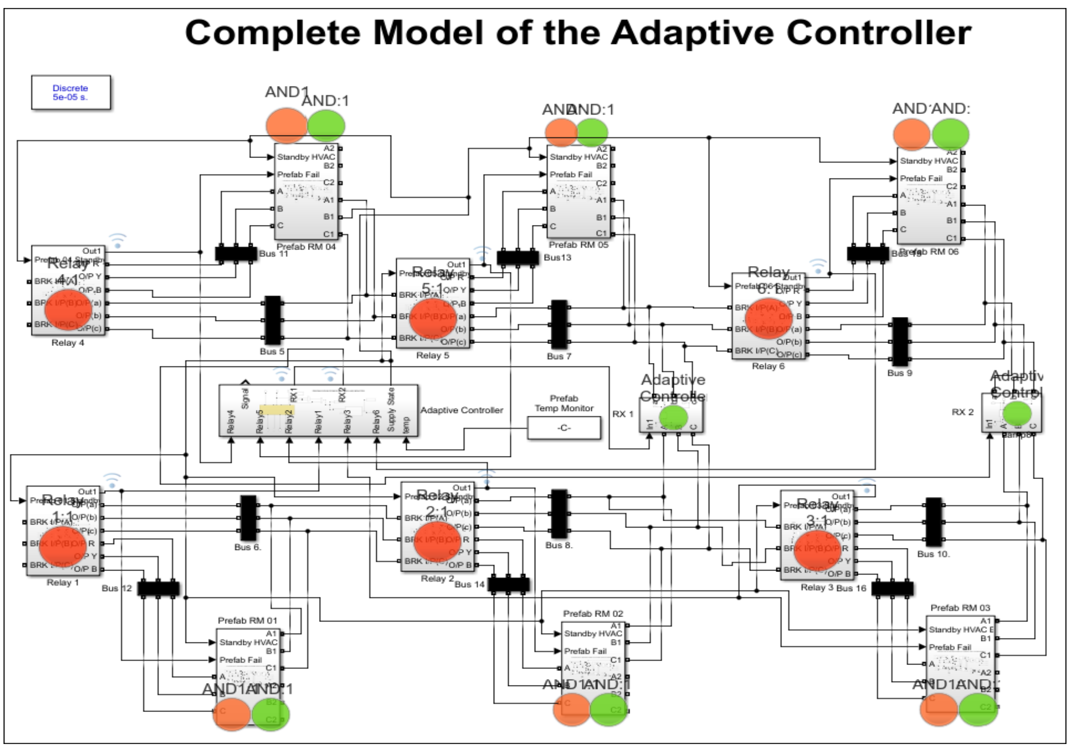

Figure 18: Complete model of the Adaptive Controller

Vol. 3, No. 6 | 2022 | pp. 1-26 | *DOI: https://doi.org/10.5281/zenodo.7413430*

To Integrate the Entire System and Simulate

After interconnecting the different models that make up the adaptive controller, Figure 19 show the model of the adaptive controller integrated into the model of the network for the overall system to be simulated so as to evaluate its performance and improvement achieved. All the signals, voltage and current levels were monitored through the graphs and visual indication lamps to monitor the performance of the controller and its ability to quickly isolate fault locations, restore power to the healthy part of the network as well as powering the standby cooling unit in the failed prefab to ensure cooling is restored to avert heat buildup which leads to total or partial disruption of services.

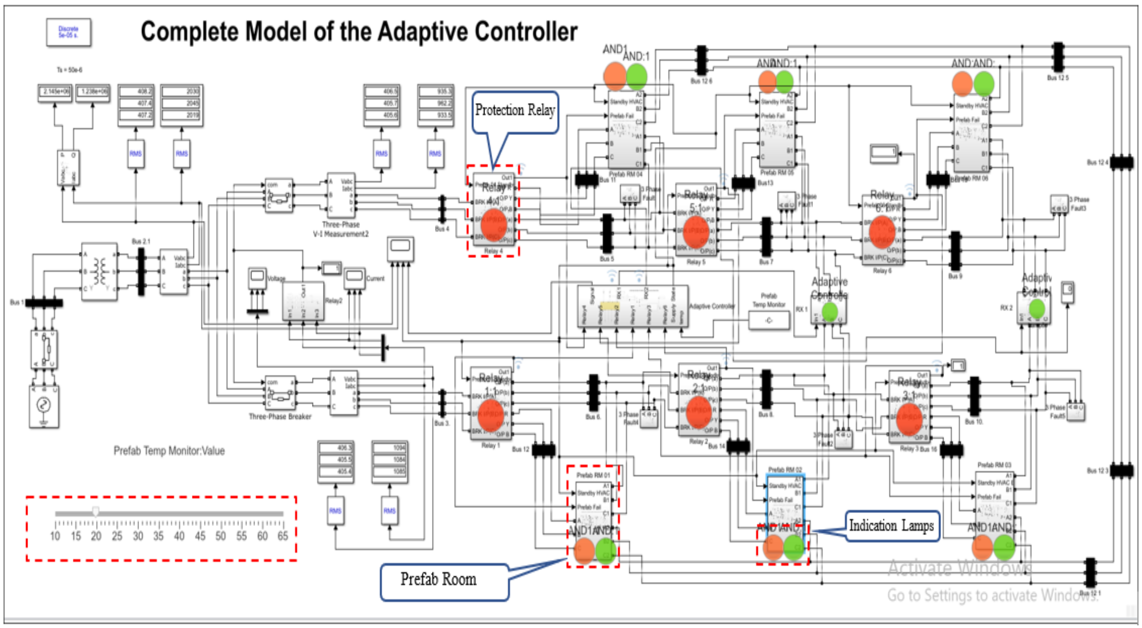

Figure 19: Model of the Adaptive Controller Integrated into the Network

This was done to assess the suitability of the controller to perform urgent cooling interventions necessary to ensure cooling quickly restored to avert heat buildup which predispose the network nodes and servers to emergency shutdown due to premature equipment failure, equipment functionality impairment or total/partial services downtime due to the rapid rising room temperature during a distribution fault. The below capture shows the completed model simulated with a three-phase line fault on Relay 1 which feeds Prefab 01.

Data Presentation

Table 2: Reliability Report of MTN Enugu Switch Power & Cooling

S/N.	INFRA TYPE	LOCATION	RELIABILITY	FAILURE RATE	MTBF
1	MAINS + AVR + DG	RAW POWER	99.97%	0.000000403	2,481,390
2	UPS	UPS POWER	99.99%	0.000134415	7,440
3	MAINS + AVR + DG + UPS	RAW POWER + UPS	99.96%	0.000000537	1,862,197
4	COOLING	PREFAB 01	91.03%	0.000126318	7,917
		PREFAB 02	89.78%	0.000144903	6,901
		PREFAB 03	93.76%	0.000086601	11,547
		PREFAB 04	91.02%	0.000126466	7,907
		PREFAB 05	91.02%	0.000126466	7,907
		PREFAB 06	92.22%	0.000108860	9,186
5	COMBINED COOLING	PREFABs (01 – 06)	58.54%	0.000719704	1,389

The result presented in Table 2, shows that the reliability values of the raw power which is comprised of the mains supply, the AVR and the three units of 1.5MVA diesel generators (DG) is 99.97%. When this was combined with the UPS which powers the PDUs on which the servers are connected, the combined raw power and conditioned power (UPS) gave us 99.60%. Also, when the prefab cooling reliability was evaluated for the same period, it was discovered that prefab 02 which is one of the oldest prefabs performed the least with reliability of 89.78% while prefab 06 had the best reliability of 92.22%.

The reliability report of prefab 02 tells us that after a one-month cycle of 744hrs which is the normal maintenance cycle of the HVACs, there is an 89.78% chance that the cooling units in prefab 02 will continue to sustain cooling capacity or continue to work optimally. However, when the combined cooling reliability of the prefabs was evaluated, the result was very low at 58.54% which suggests further that only 58.54% of the prefab rooms can sustain cooling after a one-month cycle period. The reliability concerns from the report show repeated supply breaker failure, failed compressors, and condenser fan motor.

Table 3: Average of the Prefab Temperature Rise Vs. Time

All Prefab Rooms	Time for temp rise from 22°C to 25°C (Mins)	Time for temp rise from 25°C to 30°C (Mins)	Time for temp rise from 30°C to 45°C (Mins)	Time for temp rise from 45°C to 60°C (Mins)
Average	**2.8mins**	**7.2mins**	**12.83mins**	**17.5mins**

Additionally, the change in temperature over time in all the prefab rooms was monitored during a power changeover from mains supply to DG1, DG2 or DG3, there is temporary power loss to the cooling equipment (HVACs). Table 3 presents the average of the Prefab temperature rise over time during a power outage and shows that while the standby DG is expected to start and load in less than one minute, it takes only about 2.8minutes for the temperature to rise from 22 to 25°C, 7.2 minutes to rise from 25 to 30°C, 12.83 minutes to rise from 30 to 45°C and for the last consideration, it took 17.5minutes to rise from 45°C to 60°C.

This report calls for a very strict preventive maintenance program for the cooling HVACs especially during the heat seasons of the year to ensure that cooling capacity is sustained all through.

Additionally, tree-phase and ground fault test, phase-to-phase fault test and single-phase and ground fault test were simulated to see the ability of the Adaptive controller to achieve urgent cooling interventions during a power distribution fault by safely isolating the fault section of the distribution network and restore power to the healthy part of the distribution. During the test, time of restoration of power to the standby cooling equipment from the healthy part of the distribution was equally monitored.

Adaptive controller test result: Fault in Prefab 1, between R1 & R2

The schematics of the operations are presented below and highlighted, take care to notice the colour change on the relay status indication lamp and prefab status indication lamps for all the simulation as these provide visual indications of the operational status of the relays during the simulation. The R1 fault current ***F*** is the difference between the pickup current I_P and preset relay current I_S. Figure 21 shows the current captured on Relay 01 (R1) just before the trip.

Vol. 3, No. 6 | 2022 | pp. 1-26 | DOI: https://doi.org/10.5281/zenodo.7413430

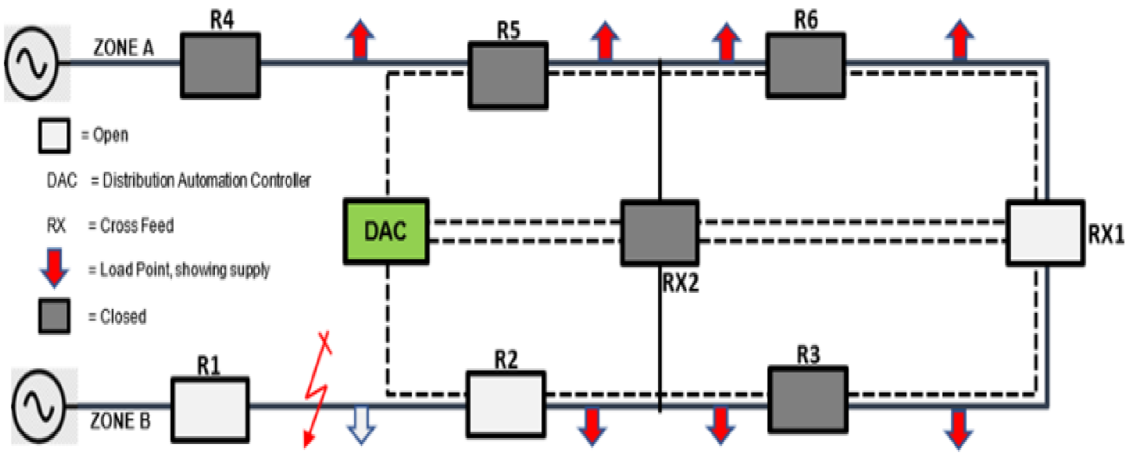

Figure 20: Prefab 01 fault, between R1& R2, with R1 tripped

During this test, IP was 1139A while IS was observed to be 910A, this implies that F = (IP - IS) was observed to be 229Amps which is higher than the preset maximum current for the normal operation defined for R1.

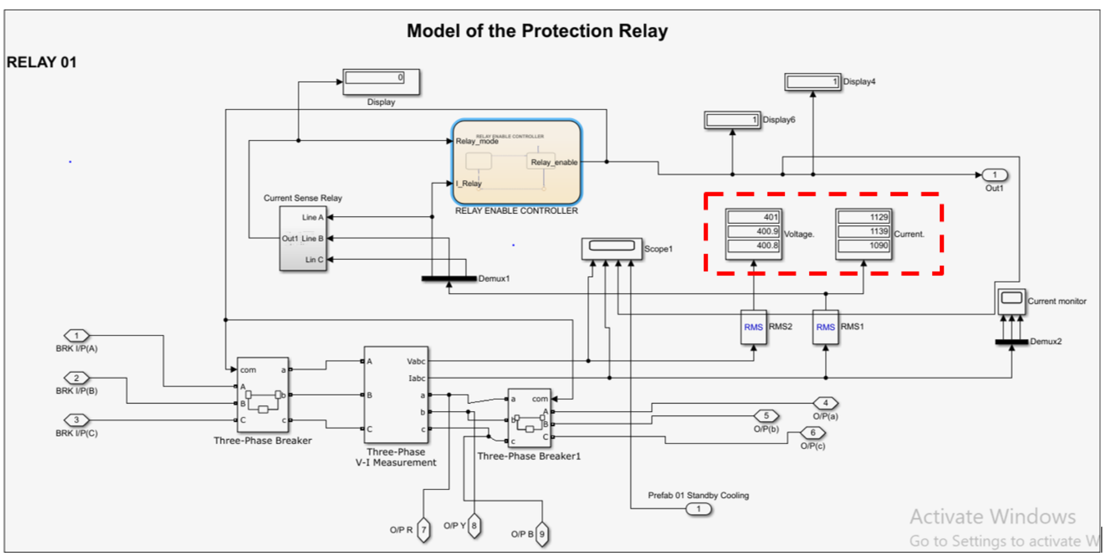

Figure 21: Prefab 01 (R1) Load Current Before Trip

Table 4: Summary of Restoration Time During Fault Simulation Test

SIMULATION OF LV DISTRIBUTION FAULT RESTORATION TIME WITH THE PROTECTION RELAY

FAULT TYPE	Protection Relay	Fault Time (ms)	Isolation Time (ms)	ΔT(ms)
3 PHASE AND GROUND	R1	300	317	17
1 PHASE AND GROUND	R1	300	320	20
PHASE TO PHASE	R1	300	320	20
AVERAGE		**300**	**319**	**19**

After the successful completion of the fault tests on the Protection relay, Table 4 presents the test results and shows that it took an average of 19ms to isolate the three fault types tested which is by far less than the 2 minutes required for efficient cooling intervention during distribution fault.

The Prefab rooms were tested to see the suitability of the developed Adaptive controller to mitigate cooling failure during LV power distribution fault. Note that the service indication lamp on RX2 changed from Green to Red immediately it was energized. At this

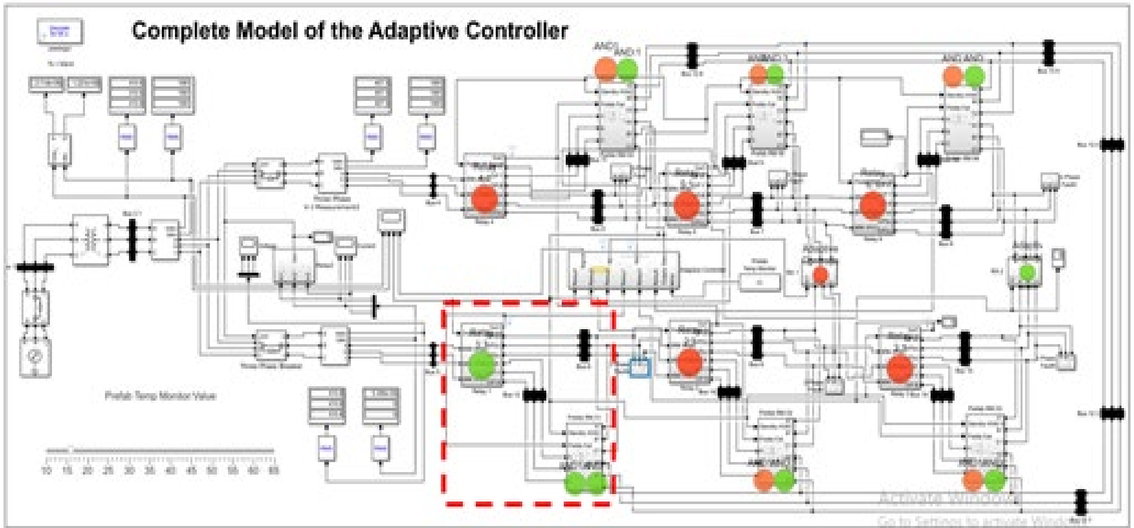

Figure 22: Power Distribution Fault Affecting Relay 1 And Prefab 1

Point, the adaptive controller checked the closest prefab with a healthy supply and connected the standby cooling unit to recover cooling. The temperature monitor continued to monitor while cooling recovery is sustained.

As shown in Figure 23, the prefab indication lamp point transitions from GREEN to AMBER to indicate that there is an active fault in prefab room 01. It was also observed from the graph of Figure 24 that the fault occurred at 300ms, was isolated at 316ms while the standby HVAC in prefab 01 was powered on the healthy part of the distribution network at 375ms.

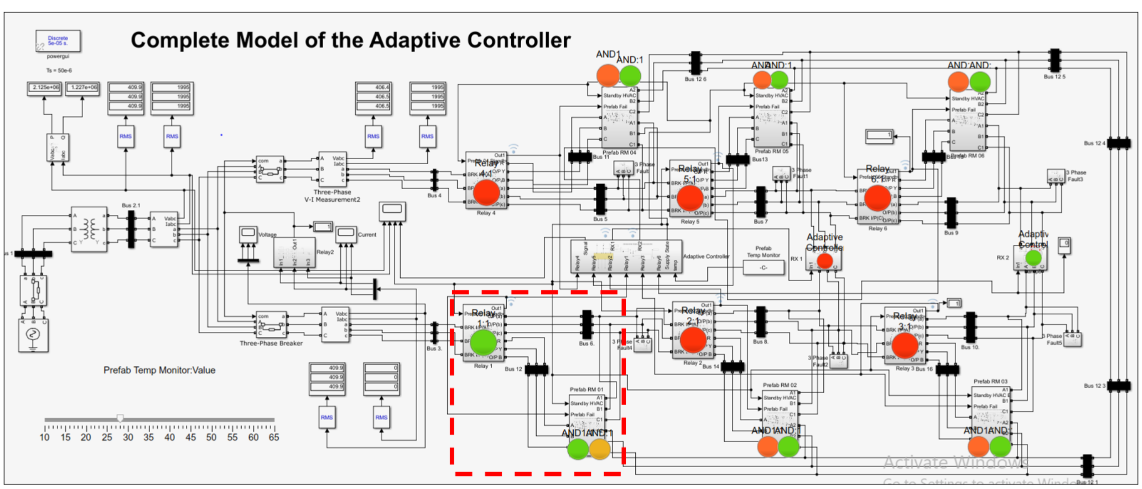

Figure 23: Standby HVAC in Prefab 01 Restored After Fault Isolation.

This implies that the time for the protection relay to isolate the fault was 16ms from the time of fault, the time between the isolation of fault and powering of the standby HVAC is 58ms and time between the fault and loading of the HVAC is 75ms. The observed switching frequency from the graph is 17.17Hz.

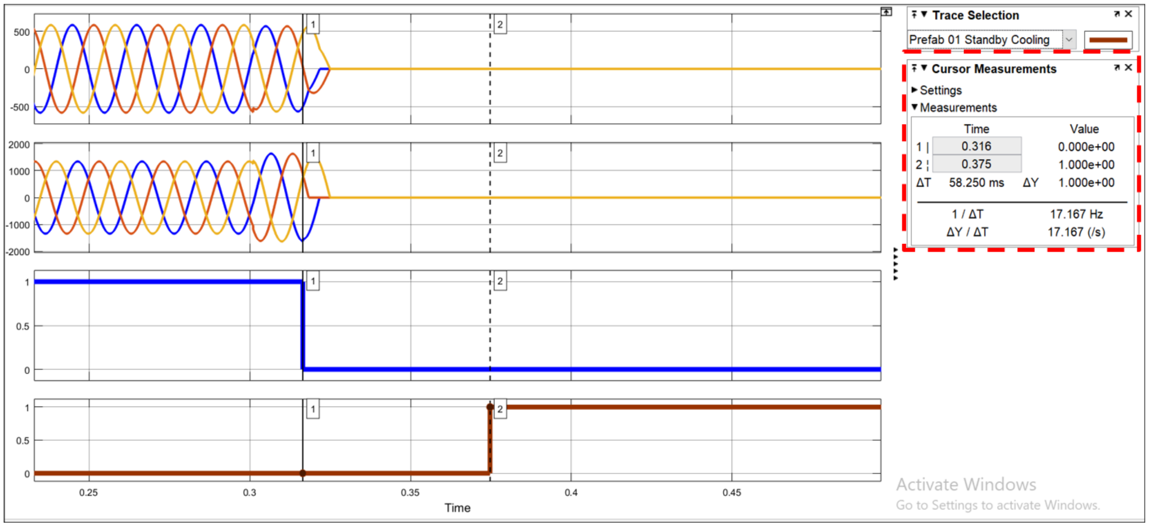

Figure 24: Prefab 01 (R1) V-I Waveforms, and Control Signals Before and During the Fault.

After successful completion of the fault tests on each of the prefab rooms to validate the suitability of the adaptive controller to provide efficient cooling intervention during power distribution fault or cooling failure.

The test result is presented in Table 3 and 4 and shows that it took an average 14ms to isolate distribution fault on any of the prefab rooms, 148ms to supply the standby HVACs in the affected prefab room from the healthy part of the distribution and a total of 162ms from time of fault to cooling intervention which is by far less than the 2minutes presented in Figure 5 and Table 2 required for efficient cooling intervention during power distribution fault or cooling failure.

Table 5: Average Time for FLISR and Cooling Restoration to Affected Prefab Room

FAULT SIMULATION TEST RESULT WITH THE ADAPTIVE CONTROLLER						
PREFAB	**Isolation Time (ms)**	**Cooling Restoration Time (ms)**	**Time between Fault and Isolation (ms)**	**Time between isolation and Cooling Restoration (ms)**	**Time between isolation and Cooling Restoration (ms)**	**Remarks**
PREFAB 01	316	375	16	59	75	<2mins
PREFAB 02	317	444	17	127	144	<2mins
PREFAB 03	303	638	3	335	338	<2mins
PREFAB 04	316	426	16	110	126	<2mins
PREFAB 05	317	470	17	153	170	<2mins
PREFAB 06	317	418	17	101	118	<2mins
AVERAGE	**314**	**462**	**14**	**148**	**162**	**<2mins**

Improved Outage Restoration Time

Notice the huge reduction in the outage restoration time with the introduction of the adaptive controller as presented in Figure 25

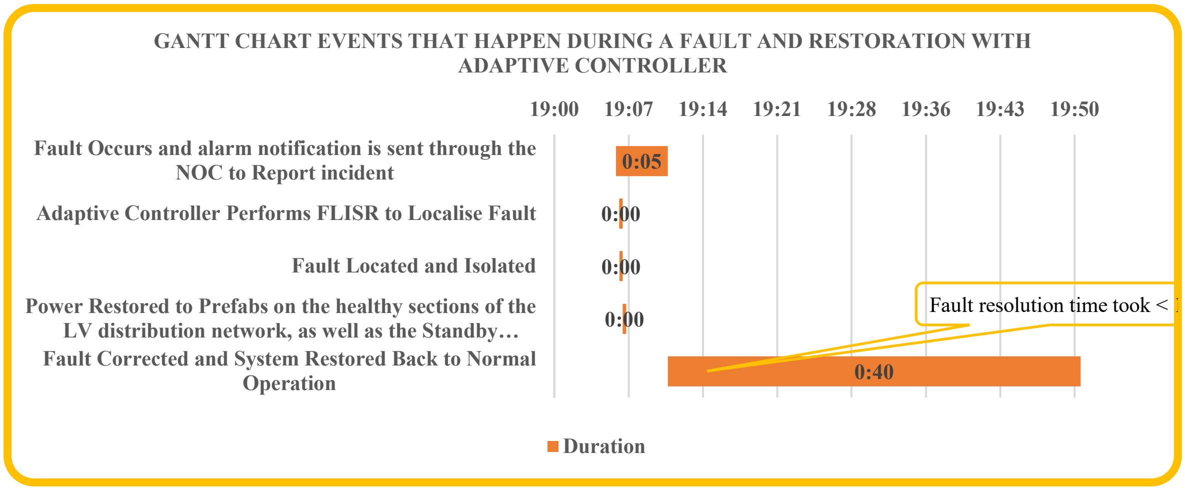

Figure 25: Power Outage Callout Event Sheet with the Adaptive Controller

The total process involved in the cooling intervention in the affected prefab room which comprised of fault location, isolation, and service restoration (FLISR) and the connection of the standby HVACs to the healthy part of the distribution network were successfully achieved in less than 2 minutes with the Adaptive controller compared to 90 minutes of fault resolution time with manual intervention presented in Figure 6.

The adaptive controller makes the power restoration to the standby cooling unit from the healthy part of the distribution network almost immediate during a distribution fault to ensure cooling is quickly recovered and sustained.

Findings

I. The passive infrastructure RBD analysis presented in Table 2 shows that the combined reliability, MTBF and failure rate (λ), of the raw and conditioned power is 99.96%, 1,862,197hrs and 0.000000537 respectively. Similarly, the combined cooling reliability, MTBF and failure rate (λ), was observed to be 58.54%, 1389hrs and 0.000719704 respectively. Further analysis shows that after 250hrs, the reliability of the raw power is 99.989% and reduces further to 99.97% after 744hrs. This is within the acceptable range for the data center. However, for the cooling infrastructure, the reliability at 250hrs is 83.53% and reduces further to 58.54% after 744hrs. This result is far below the data center cooling requirement and recommendation by ANSI/TIA and suggests that there is a 58.54% chance that the cooling units in the prefabs rooms will continue to work optimally after a period of 744hrs (1-month cycle) if preventive maintenance is not done.

II. All the electrical power consumed in a data center is transformed into heat and under normal operating conditions, the heating rate must be balanced by an adequate rate of cooling. Also, during a power loss, it takes only about 2.8minutes for the temperature to rise from 22 to 25°C, 7.2 minutes to rise from 25 to 30°C, 12.83 minutes to rise from 30 to 45°C and 17.5minutes to rise from 45°C to 60°C.

III. The analysis of the power outage callout event log without the adaptive controller presented in Figure 6 shows that the traditional manual intervention during a power distribution fault required a minimum of 65 to 90mins of cooling restoration time which is by far higher than the 2mins determined through experiments presented Figure 5 and Table 1.

IV. Urgent cooling interventions between the first 2 minutes of the power failure will help reduce the heat spike that happens around the 7th minute of a cooling failure since the cold air is still trapped under the raised floor and can be circulated by the fan of the standby cooling equipment before the compressor starts.

V. BESS used by UPS and DC rectifiers systems play critical roles in keeping essential IT equipment functional during a power outage. These backup batteries operate efficiently when stored around 20 - 25°C and are able to discharge at a normal rate. Efficient use of the BESS battery autonomy during a power outage is usually restrained by the heat buildup which takes less than 20 mins from outage time to attain elevated temperatures above 55°C. At this elevated temperature, above the 18 to 22°C recommended by ASHRAE, the IT equipment which should remain connected to the UPS PDU or DC plant RDU for a minimum of 8 –

10hrs, begin to freeze or shutdown to avert premature equipment failure because of the unacceptably high temperatures in the affected prefab room.

VI. The proposed adaptive controller was able to perform FLISR on the switch LV distribution network by localizing power distribution faults, safe isolation of the affected prefab room (fault section), and restoration of power to the healthy part of the network as well as to the standby HVACs in the affected prefab room. The FLISR function and cooling restoration is completed in less than 2mins of the outage as presented in Figure 6 to quickly recover and sustain cooling in the affected prefab.

Contribution to Knowledge

This research outlines how the developed adaptive controller can avert total or partial services disruption during a cooling outage following a power distribution fault in any of the prefab rooms and explains each of the different models that make up the adaptive controller – the protection relay, the temperature controller, the cooling intervention controller, and the controller logic as well as their combined role towards achieving an efficient cooling intervention.

The power outage callout event log presented in Figure 6, shows that it is only with the adaptive controller that urgent cooling interventions can be achieved in a mobile switching center. It further shows the type of intervention that should be done and specified that such intervention must be capable of FLISR. Similarly, the data presented in Table 3 and the temperature-time graph presented in Figure 5 shows from experimentally determined data, how quickly this intervention should be done and, specified that standby HVACs must be restored in less than 2 minutes of outage since it takes up to 8mins for the compressors to start. This further shows that only 10 minutes is required to sustainably manage cooling failure during a power distribution fault.

The developed adaptive controller can be implemented in any telecommunications room where cooling is critical for optimum operation.

Conclusion

This research was successfully completed with all the research objectives achieved and developed into the model of the Adaptive controller. The results of the characterization presented in Table 4, 5 and the RBD analysis shows that in a one-month maintenance cycle of 744hrs, there is 89.78% chance that the cooling units in prefab 02 will continue to work optimally. Also, the combined cooling reliability of all the prefab room result was 58.54% at 744hrs which suggests that only 58.54% of the prefab rooms can sustain cooling after a one-month cycle period. Further checks on the combined cooling reliability gave 83.53% at 250hrs for same failure rate which calls for urgent and stringent maintenance programs developed for 250hrs cycle in addition to the already existing 744hrs cycle. This should be proactively applied to the cooling units on a need basis to increase the MTBF and the reliability of the older units, especially during the heat season of the year to 99.982% required for high performance and public safety as specified by ANSI/TIA.

Similarly, the characterization results presented in Figure 6, show the type of intervention that should be done during a power distribution fault in the mobile switching center and specified that such intervention must be capable of FLISR. Table 1 and Figure 5 showed from experimentally determined data, how quickly this intervention should be done and specified that standby HVACs must be restored in less than 2 minutes of outage since it takes up to 8mins for the compressors to start which further shows that only 10 minutes is required to sustainably manage cooling failure during a power distribution fault.

The test results of the Adaptive controller show that a total of 162ms is the average time from time of fault to cooling intervention which is by far less than the 2minutes maximum time presented in Figure 5 and table 2 required to provide an efficient cooling intervention during power distribution fault or cooling failure. This test result shows an improvement in MTTR from about 90 mins to < 2 mins and validates the ability of the developed adaptive controller to improve the overall system reliability by mitigating the impact of cooling failure in any of the mobile switching center prefab rooms.

Lastly, this Adaptive controller can be implemented in any telecommunication room where cooling is critical for optimum operation.

Recommendations

Future work on cooling improvement in the data center should look at ways of applying predictive analysis to the model in such a way that current and temperature of the circuit breakers supplying the cooling equipment are monitored alongside the room temperatures so that deviations from normal values can inform decisions on the type of maintenance that will improve reliability.

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APPENDIX 1: MTTR, MTTF, MTBF and System Failure Rate (λ) for the HVACs in MTN Switch prefab rooms

S/NO.	NAME	SERVICE LOCATION	NUMBER OF FAULTS	SERVICE HOURS /ANNUM	OUTAGE HOURS	AVAILABILITY BASED ON SERVICE HOURS	MTTF	MTTR	MTBF	SYSTEM FAILURE RATE (Λ)	SYSTEM REPAIRE RATE (M)	RRLIABILITY FOR 1YR (8760HRS)
1	A1	UTILITY SUPPLY	2	8716	44	99.50%	4358	22	4380	0.0002283	0.05	84.38%
2	A2	AVR	1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%
3	B1	GEN 01	2	8698	62	99.29%	4349	31	4380	0.0002283	0.03	84.38%
4	B2	GEN 02	1	8758	2	99.98%	8758	2	8760	0.0001142	0.5	91.86%
5	B3	GEN 03	1	8758	2	99.98%	8758	2	8760	0.0001142	0.5	91.86%
6	CU1A	PREFAB 01	2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
7	CU1B		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
8	CU1C		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
9	CU1D		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
10	CU1E		2	8752	8	99.91%	4376	4	4380	0.0002283	0.25	84.38%
11	CU1F		1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%
12	CU2A	PREFAB 02	2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
13	CU2B		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
14	CU2C		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
15	CU2D		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
16	CU2E		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
17	CU2F		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
18	CU3A	PREFAB 03	2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
19	CU3B		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
20	CU3C		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
21	CU3D		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
22	CU3E		1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%
23	CU3F		1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%
24	CU4A	PREFAB 04	2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
25	CU4B		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
26	CU4C		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
27	CU4D		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
28	CU4E		1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%
29	CU4F		2	8752	8	99.91%	4376	4	4380	0.0002283	0.25	84.38%
30	CU5A	PREFAB 05	1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
31	CU5B		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
32	CU5C		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
33	CU5D		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
34	CU5E		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
35	CU5F		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
36	CU6A	PREFAB 06	1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
37	CU6B		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
38	CU6C		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
39	CU6D		1	8759	1	99.99%	8759	1	8760	0.0001142	1	91.86%
40	CU6E		2	8759	1	99.99%	4379.5	0.5	4380	0.0002283	2	84.38%
41	CU6F		1	8752	8	99.91%	8752	8	8760	0.0001142	0.13	91.86%