CHALLENGE-BASED MODULE

DEMAND MANAGEMENT FOR POWER-CRITICAL OFF-GRID INDUSTRIAL APPLICATIONS

FINAL REPORT

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1. Executive summary[1]

DMSystems is a low-cost integrated solution for critical applications that depend on a reliable source of power. The project is centered around a simulation-based approach that can be translated into a working product using the appropriate hardware. This report includes a working methodology based on collaborative and interdisciplinary principles; the system design based on NASA's System Engineering Handbook; preliminary calculations, modeling, and simulation performed on MATLAB and Simulink; and the first elements of a socio-economic analysis.

The desire to build this type of integrated solution originates from industrial needs, specifically in the mining sector in the Middle East. The mining application under consideration experiences sporadic power outages due to unexpected reduction in power generation availability. The remote nature of the mining application, unreliability of diesel generators, and intermittency of renewable energy sources imply that a straightforward solution may not exist. Moreover, existing solutions such as adding redundancy by increasing the number of diesel generators, or incorporating energy storage can be financially infeasible, wasteful, and polluting in many cases.

A fast-response demand-management system such as *DMSystems* has the potential to solve the problem of power reliability for the mining application, and consequently, many other applications that depend on a reliable source of power but cannot afford redundancy, including off-grid industrial applications and hospitals in remote locations especially in the developing world. The system can be easily installed in existing electrical infrastructure with minimal modifications, and a user friendly visual interface ensures that the end user can understand and operate the system with minimal training, increasing its accessibility and penetration into many markets worldwide.

The results from the simulations demonstrate that the system can respond to reduced power generation availability identified in the form of declining system frequency below a defined threshold within a desired roundtrip response time of 10 milliseconds. In addition, the financial assessment indicates that the operational expenditure of the demand-management system would be around 80% cheaper than adding redundancy. Environmental benefits of the system are also evident in the form of reduction in primary and secondary emissions due to the lower use and presence of diesel generators as redundancy.

There is an urgent call for action to recognize that ending poverty must go hand in hand with strategies that improve health and education, reduce inequality, and spur economic growth while tackling climate change and working to preserve our oceans and forests [1]. *DMSystems* has the potential to help tackle at least seven Sustainable Development Goals (SDGs) while serving as a sustainable and cost-effective solution for the industry. Therefore, it is anticipated that this solution would receive more attention in the future, and this report further evaluates this central idea.

[1] The terms of the non-disclosure agreement (NDA) signed between DENSYS, and the involved industrial partner prohibit public dissemination of specific details about this project. Some information has been intentionally excluded in this report to prevent violation of the NDA.

2. Introduction

This project aims to tackle the issue of power reliability due to unexpected reduction in power generation availability in remote off-grid industrial applications. Although the case study under investigation is a part of the mining industry in the Middle East, the solution is expected to be applicable to all cases that are affected by similar issues. Given their remote nature and lack of access to a stable local power grid, plants in the mining industry are typically powered by diesel generators. Unexpected loss of power often halts the functionality of the entire plant. A power outage that lasts no longer than 15 seconds could bring the entire operation of the plant to a standstill for up to 30 minutes. This is because rocks that are trapped in the machinery at the time of the power outage can only be removed with the use of heavy lifting equipment like a crane. Therefore, ensuring that the priority loads always receive their required power is crucial for the operation and business as the failure to do so brings with it time and financial losses.

The power needed by the mining application in this project is supplied by diesel generators as well as photovoltaic (PV) panels. To ensure reliability and guard against unexpected power outages, backup diesel generator units are present on-site. The major downside to this is the cost incurred in paying for the redundant units that may not be used regularly. A second strategy is to preserve a conservative 'spinning reserve' on the diesel generators. This corresponds to the unused capacity of the generators. The greater the spinning reserve, the more power available as an insurance policy during an outage. However, this does not represent the most optimal utilization of the diesel generators. A third option to improve reliability is with the incorporation of a battery energy storage system (BESS). Although a promising alternative, this involves significant upfront investment cost increasing the financial risk for the project.

Aside from the three possible solutions involving power generation mentioned above, the reliability of the system can also be maintained by controlling the loads. With this alternative approach, the load shall be reduced to the extent of the capacity of the power generation unit that is out of order. A solution of this nature will prolong the time available to restore power generation to its maximum capacity as the running units will still be able to supply sufficient power to the active loads. This would help avoid a spontaneous power failure that would lead to a halt in the entire operation of the facility. The process of disconnecting non-priority loads can be carried out manually by assigning a dedicated operator for the job or by automating the decision using a demand-management system. The definition of 'non-priority' in this context refer to loads that are not critical in the operation of the facility. In the case of the mining application, these may include smaller mining machinery, air-conditioning units, pumps or refrigerators.

This enables the following hypothesis for this project to be formed - a fast-response, autonomous demand management / load shedding mechanism with a time response of 10 milliseconds can improve power reliability of off-grid industrial applications.

3. Methodology

The following project management tools were used and are shown in Appendix A.

1. Project milestones and deliverables detailed in a work breakdown structure (WBS) with an identified critical path.
2. Task sharing among the group outlined by a responsibility assignment RACI (Responsible Accountable Consulted Informed) matrix.

In addition, the memo of a meeting has been shown as a sample in Appendix B.

The specific role of each member of the team consists of a set of tasks described in the work breakdown structure of the project. These tasks are assigned based on each member's background and interests. To ensure proper management of the overall project and foster leadership skills, a "rotating leadership" scheme has been implemented involving 3 members at a time – a project leader handling administrative tasks such as calling for the meetings, emailing / contacting the supervisors and making sure that all tasks are completed on time; a project manager looking after the technical coherence of the decisions taken / options considered; and a reporter updating the meeting minutes as necessary. The individual in each role changes every 2 months based on a random draw. The benefits of such a scheme include an opportunity for each member to practice and develop their own project management style and a diverse range of leadership approaches that can only bring added value to the design of the demand management system.

4. System Design

Adopted from the NASA Systems Engineering Handbook[2], the system design processes are interdependent, highly iterative and recursive processes that result in a validated set of requirements and a design solution that satisfies a set of stakeholder expectations. It consists of four stages – stakeholder expectations, technical requirements definition, logical decomposition, and design solution definition.

4.1. Stakeholder expectations

An identification of all the stakeholders involved in the project coupled with a clear understanding of their needs, goals, and objectives, predefined constraints, as well as criteria for success constitutes an effective blueprint for this project. The list of stakeholders involved, and their respective roles are explained below.

1. **Academic supervisors:** The stakeholders to whom the student project team consult most of the work, present their ideas, report progress, and seek feedback to make the work more efficient and ensure that it proceeds in the right direction. They provide both technical and non-technical expertise involving the design of the controller and communication system to ensure the optimal solution can be realized within the allocated timeframe. The academic supervisors determine whether the devised simulation-based solution can be implemented in the real-world while deliverables such as reports meet the expected learning outcomes. They strive to facilitate a holistic, interdisciplinary and collaborative learning experience during which the student team learns multiple new transferrable skills and delivers a project that fulfills all the requirements set by the industrial partner.
2. **Industrial partner:** This stakeholder is an energy management company that specializes in the provision of reliable and cost-effective distributed power for off-grid applications in the Middle East. It powers the mining application that this project is focused on. This company uses innovative engineering technologies to improve reliability of power and strives to eliminate the likelihood of unexpected power outages in a cost-effective manner. The incorporation of an autonomous demand-management strategy would enable the company to reduce operational cost by decreasing redundant capacity for power generation and also avoid paying compensation to its client for any revenue lost as a result of these unexpected power outages. The industrial partner provides crucial practical information related to the problem to both the students and academic supervisors as well as insights into the current solutions on-site, specific objectives, and practical feedback on the actual work carried out.
3. **Mining application:** This entity has hired the industrial partner as a service provider to power the infrastructure of the mining application. Interruptions to the power supply that last even a matter of seconds can result in significant loss of revenue for the facility. While this stakeholder has little interest in the technological elements used in the provision of power by the industrial partner, it would envision a simple and safe solution that does not interfere with daily operations at the plant. It is also important that the added reassurance in reliability of power does not translate to a higher cost of electricity.

[2] https://www.nasa.gov/seh/4-design-process

4. **Student team:** The student project team is responsible for the execution of the project. By immersing themselves in an unfamiliar real-world problem, they expect to gain both technical knowledge and the maturity to navigate different challenges with relative independence. They would be focused on developing an effective design solution considering the requirements of both the industrial partner and academic supervisors, while also keeping in mind factors such as cost and socio-economic impact. At this stage of the project, they are constrained by a relative inadequacy in information from the industrial partner given their inexperience in some of the highly technical elements but also due to concerns in public dissemination of confidential information related to their services to the mining application.

4.2. Technical requirements definition

This section focuses on the derived and allocated requirements in terms of function, performance, interface, standards and regulations, operation and safety of the demand management system collectively from the perspectives of all the stakeholders listed earlier.

The demand management system must be able to detect a spontaneous decrease in power generation availability and act on it by disconnecting non-priority loads **within a response time of 10 milliseconds**. The system itself must not consume too much power and should be relatively cheaper compared to other solutions such as increasing power generation redundancy. It must be a robust product that is easy to operate and maintain. The definition of a robust product in this case is one that reassures reliability, data security and privacy to ensure that unauthorized access to any confidential data is always prevented, and the implementation of the necessary protocols to manage and mitigate such risks. Additionally, training must be arranged on troubleshooting, the presence of a dedicated support team, and the development of a real-time monitoring system. The interface of this monitoring system must be straightforward and user friendly. Furthermore, the necessary training must be provided on the basic functionality of the system that would be relevant in the unlikely event of the unavailability of the industrial partner. Moreover, any local regulations for such electrical systems must be adhered to. The system must also not cause any defects to the existing electrical equipment on site. It must also be appropriately enclosed and isolated to prevent unauthorized physical access and prevent safety hazards to authorized personnel that access it.

4.3. Logical decomposition

Logical decomposition is the process of creating the detailed functional requirements that enable projects to meet the stakeholder expectations. This process identifies the "what" that should be achieved by the system at each level to enable a successful project. Logical decomposition utilizes functional analysis to create a system architecture to decompose top-level requirements and allocate them down to the lowest desired levels of the project. Functional analysis is the primary method used in system architecture development and functional requirement decomposition. It is the systematic process of identifying, describing, and relating the functions a system should perform to fulfill its goals and objectives. Functional analysis identifies and links system functions, trade studies, interface characteristics, and rationales to requirements [2].

Before performing the functional analysis of the controller, a short but clear description of the system where the controller is embedded is provided. Understanding this system is crucial, it allows to put into perspective the stakeholder expectations and the technical requirements definition. With this information, a functional analysis based on the TRIZ approach is performed. The result is a set of challenges based on the expected user experience for each of the relevant stakeholders. These challenges form the foundation for synthesizing a solution in this project.

Description of the industrial plant[3]

As shown in Figure 1, the generators are connected directly to a centralized low voltage (LV) panel. From here, multiple runs of cable are connected to the low voltage side of 3 individual transformers. For simplicity, the three different transformers are considered as one transformer.

From the transformer, the voltage is stepped up from 415 V to 11 kV, which is then sent to the loads via a ring main unit (RMU), with circuit breakers at both ends. An RMU is a set of switchgear used at the load connection points with switches that connect both ends of the load [4].

From the previous RMU, power is sent to another RMU and another transformer steps it down to 415 V. From the three transformers, all low voltage cables are connected to a main low voltage panel via air circuit breakers (ACBs). This main low voltage panel has multiple ACB outgoers to main distribution panels with ACB incomers and multiple MCCB outgoers.

There are three primary and two secondaries in the system, each has its own panel, and each panel is split into multiple outgoers powering the individual loads. The location of this LV panel is about 1.5 km away from the generation point. The number, description, and the priority assigned to each type of loads (that determine the order of disconnection) are described in

Table 1.

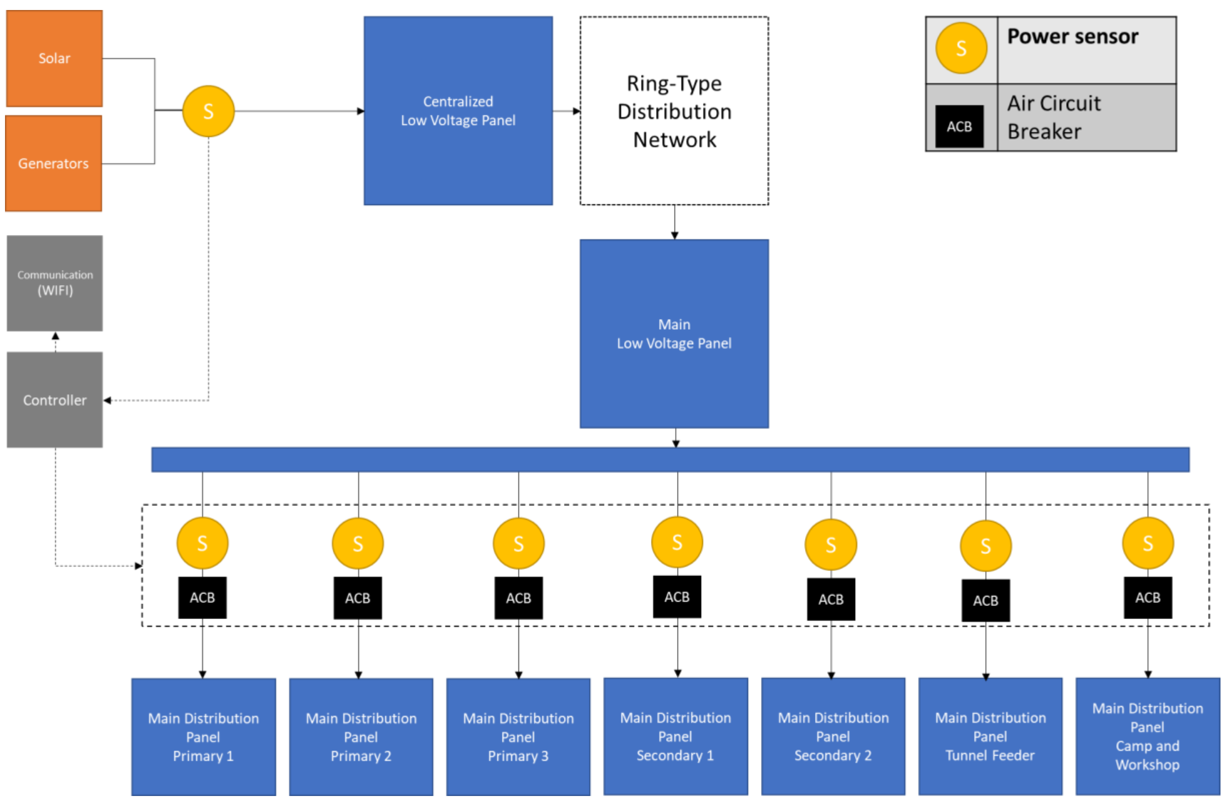

Figure 1: Block diagram of the industrial plant

[3] Based on information provided by the industrial supervisor
[4] https://www.lucyelectric.com/what-is-a-ring-main-unit

A detailed single line diagram (SLD) depicting the electrical setup of the plant is shown in Appendix D.

Table 1: Loads, power consumed and priority of each load. A value of 1 indicates maximum priority (last to be disconnected), a value of 5 indicates least priority (first to be disconnected)

Main Distribution Panel	Load	Priority
Primary 1	362 kW	1
Primary 2	433.8 kW	2
Primary 3	419.4 kW	1
Secondary 1	1,653 kW	4
Secondary 2	234.1 kW	4
Tunnel Feeder	50 kW	5
Camp and Workshop	400 kW	3

4.4. Functional analysis

The following functional analysis makes use of the TRIZ approach. The first step is to derive customer function. The second step is to derive the main component functions by answering the question "what functions do the main components fulfill?". The third step is to visualize the following relations between functions: "… is needed to …", "… causes …", "… was implemented to avoid …". The fourth step is to characterize the functions into useful or harmful. Finally, it should be possible to identify relevant problems that can be solved using the analysis that has just been completed [3].

Functional abstraction can be used on a service level, and it is based on the previous description of functional analysis. Five steps can be followed: "Define, cluster and choose target groups", "Customer oriented process", "Description of the process", "Functional or attributable description of the challenges", and "Identification of branches or industries with similar (functional) challenges" [3].

Define, cluster and choose target groups

During this step of the functional abstraction, the different stakeholders involved in the project are defined and characterized visually and their relation to each other are explicitly shown.

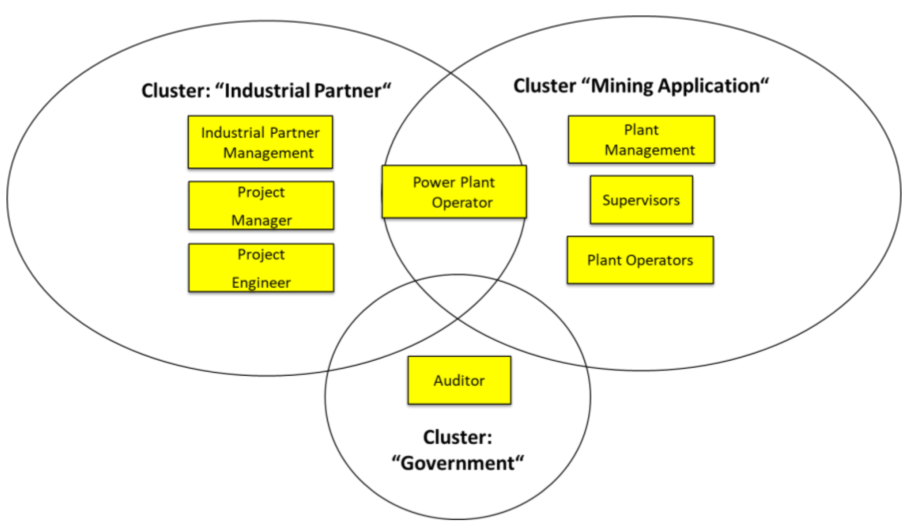

Figure 2: Defining and clustering stakeholders and target groups

User experience (UX) processes

For this step, the expected UX processes for each of the relevant stakeholders are stated in Figure 3. Each UX process is just an idea in the mind of the system architect. To make each idea a reality, several challenges must be overcome. These challenges are further described in Table 2.

UX Process	Challenges	
Process for cluster "Industrial Partner"		
Monitoring Power Plant Operation	*Design a communication interface for the controller that complies with an industry standard and a SCADA for Power Plant Operations*	
Installation	*The controller should be easy to install and configure*	
Process for cluster "Mining Application"		
Monitoring Power Plant Operation	*Design a SCADA for Power Plant Operations. It should be user friendly and easy to operate.*	
Operation	*The controller has to be effective at increasing Power reliability*	*The controller has to be built in with redundancy and reliability in mind*
Process for cluster "Government"		
Validation	*The controller has to comply with local regulations*	*The controller should to be easy to understand and validate*

Figure 3: User experience processes and their particular challenges

Description of the challenges

Table 2: Detailed description of challenges

Challenge	Description	Functional description
Design a communication interface for the controller that complies with an industry standard and a supervisory control and data acquisition (SCADA) for Power Plant Operations	For the Project Engineer and Project Manager, having a communication interface and a SCADA is crucial for monitoring the operations and performance of the Power Plant.	Implementation of communication interfaces used in industry such as Ethernet, RS232, RS485, CAN, USB, etc. Implementation of communication protocols like TCP/UDP, Modbus, etc. Design of a SCADA with parameters for power factor, energy and power, state of the system, alerts, etc.
The controller should be easy to install and configure	For the Project Engineer, the friendliness to install and configure the controller will increase his/her productivity.	Consider physical dimensions, accessibility of connections, user-friendliness of the software.

Design a SCADA for Power Plant Operations. It should be user friendly and easy to operate	For the Operator and Supervisors, the SCADA allows for managing the operations of the plant that are affected directly by the controller.	Design around user friendliness.
The controller has to be effective at increasing power reliability	For the Mining Application shareholders and management, power reliability has a direct impact on financial success.	Ensure power reliability for Mining Application by designing a load controller with a fast time response.
The controller has to be built in with redundancy and reliability in mind	For the Plant Management, a failure of the controller or any of its components should not affect Mining operations.	Seamless integration with already existing plant equipment.
The controller has to comply with local regulations	For the auditor, proper documentation has to be readily available.	Document the characteristics of the controller and its components.
The controller should be easy to understand and to validate		

5. Implementation of calculations, models, and simulations

The electrical grid under investigation is prone to sudden failure of generator units. Under these circumstances, the system will experience an overload condition in which the balance between the demand and the generated capacity can no longer be maintained. Electrical consequences of such failures include drops in voltage and frequency and power swings that could lead to system collapse and total blackout. An excess load puts a stress on the generating equipment; it slows down the prime movers, active generators, and other parts of the system as they attempt to cope with the excess load. The resulting reduced frequency could also damage sensitive electrical components of the grid.

Grid-related data provided by the industrial partner depict typical examples of failures. They include failure notifications and active power, current, voltage, frequency variations registered by the ComAp controllers overseeing the entire power generation side of the grid. Here are some samples of generator failure obtained from the grid operations on December 21, 2021.

Table 3: Overview of the state of the generators during a grid failure on December 21, 2021

	Date	Time	Controller	Pwr	Gfrq	Bfrq	Reason	Ig1	Ig2	Ig3
174	44551	1:31:29.2	C06 - SGB 1601	640.0	49.4	49.4	BOC IDMT	1272.0	1123.0	1097.0
173	44551	1:31:29.3	C04 - SGC 1615	719.0	49.3	49.3	BOC IDMT	1430.0	1332.0	1274.0
170	44551	1:31:29.4	C01 - SGB 1603	484.0	48.9	48.9	BOC IDMT	1405.0	1238.0	1320.0
141	44551	1:31:31.4	C07 - SGJ-1500	348.0	49.3	42.4	Stp GCB fail	0.0	0.0	0.0

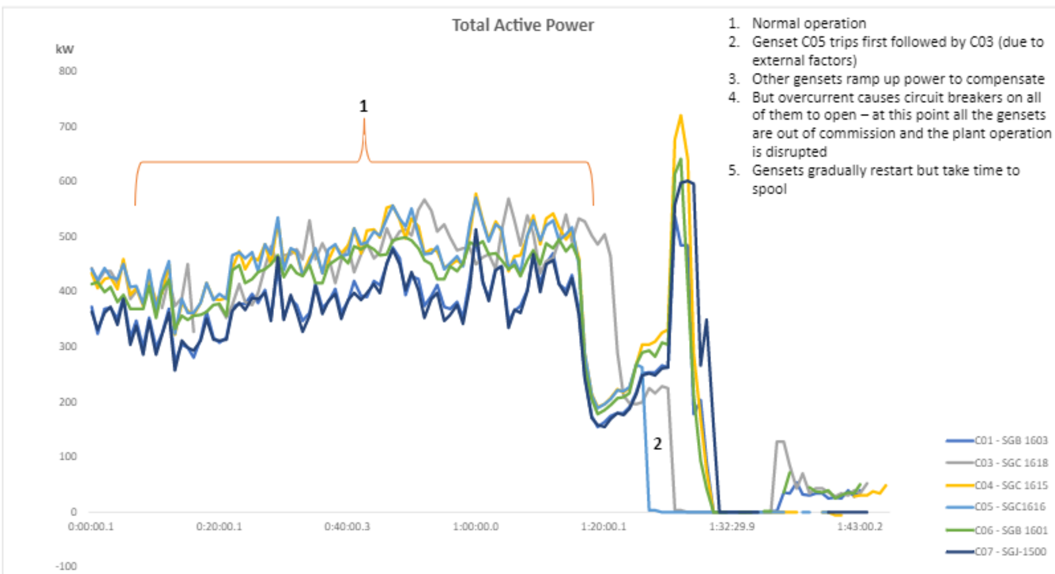

Figure 4: Active power variations of the generators during the operation period analyzed on Dec 21, 2021

The genset C03 trips first at 1:24:48.0 pm followed by CO5 at 1:25:15.1 pm and disrupts the normal operation of the grid. The remaining active gensets ramp up to compensate the lost power, which cause them to exceed the safety limits and force the ComAp controllers to open all the circuit breakers by 1:32:30 pm effectively creating a blackout. The generators gradually restart their operation several minutes (around 10 minutes) after the failure.

In the following section, the chosen mitigation strategy (fast load shedding) of the consequences of such grid overload is outlined and tested.

6. Fast Load Shedding

6.1. Frequency Control

The kinetic energy stored in the rotating parts of synchronous generators plays an important role in frequency stability. When a grid fault or large imbalance of load/generation occurs in the system, frequency starts deviating. For example, if one of the generation units trip, it creates a negative imbalance in a conventional power system, and the shortfall is initially offset by kinetic energy released by the conventional generation units, commonly known as the system's inertial response. As the kinetic energy is released by all synchronously connected generators, the speed of the rotor is reduced causing a reduction in frequency. The rate of frequency change depends on power mismatch and system inertia [4].

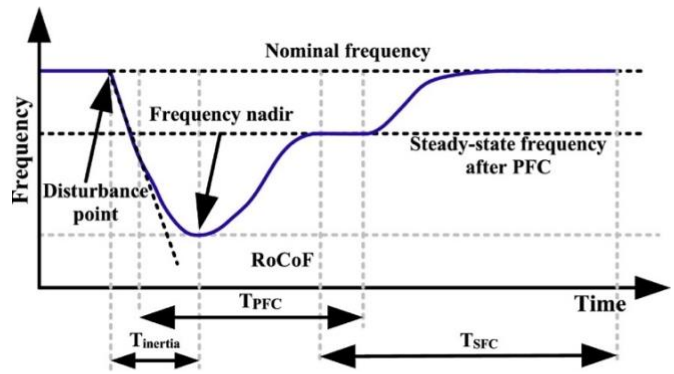

Figure 5: Frequency response and regulation of synchronous machines [4]

The drop in frequency is first characterized by the inertial response $T_{inertia}$. After some delay, the Primary Frequency Response T_{PFC} acts, incrementing the power output of the prime movers to stabilize the frequency. Finally, the Secondary Frequency Response T_{SFC} brings back the system frequency to the reference value.

Various disturbances or random deviations which impair the equilibrium of generation and demand will cause a Frequency Deviation, to which the Primary Controller of generating sets involved in Primary Control will react at any time. The proportionality of Primary Control and the collective involvement of all interconnection partners is such that the equilibrium between power generated and power consumed will be immediately restored, thereby ensuring that the System Frequency is maintained within permissible limits. In case that the frequency exceeds the permissible limits, additional measures out of the scope of Primary Control, such as Load-Shedding are required and carried out in order to maintain interconnected operation [5]. For reference, the association of transmission system operators in continental Europe defines the minimum instantaneous frequency to be 49.2 Hz (that corresponds to -800 mHz as maximum permissible dynamic Frequency Deviation from the nominal frequency), while the maximum instantaneous frequency is defined to be 50.8 Hz [6].

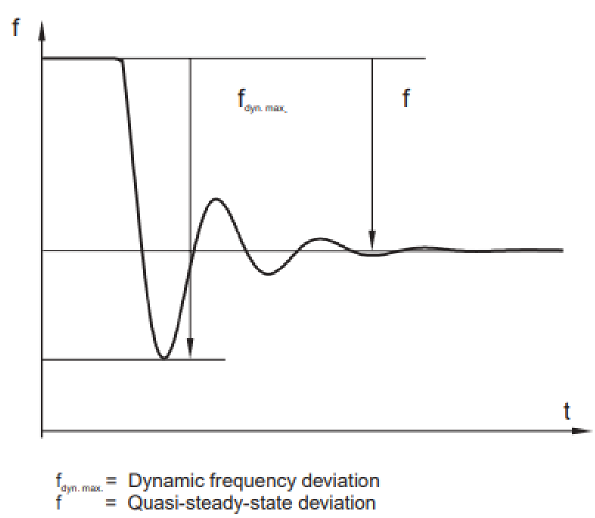

Figure 6: Dynamic and Quasi-steady-state Frequency Deviation [5]

6.2. Under Frequency Load Shedding

Under Frequency Load Shedding (UFLS) is an important measure to maintain the system frequency stability under severe disturbances. Generally, the primary objectives of UFLS are to shed an appropriate magnitude of loads to restrict frequency deviation. Adaptative UFLS schemes estimate the power imbalance by calculating the initial slope of frequency deviation and modifying shedding magnitude online to adapt to a variety of disturbances. To properly estimate the power imbalance, a supplementary algorithm is necessary to acquire the initial rate of change of frequency and the system inertial constant accurately. Inaccurate initial slope or inertia may lead to poorly estimated imbalance [7].

Generally, UFLS needs an action threshold so that the UFLS relays have the ability to avoid the occasional contingencies in which the frequency restoration can be completed with the spinning reserve capacity generation. For example, the technical rules for power system automatic under-frequency load shedding in China stipulates that the action threshold should not be higher than 49.25 Hz [8]. Frequency control for continental Europe was described in the Frequency Control chapter.

It is a common practice among power utilities to employ a conventional Under-Frequency Load Shedding (UFLS) scheme in protecting a scenario of under frequency in the grid system. The UFLS relay is set to shed certain magnitude of loads based on a specified frequency threshold. Although the scheme is simple, it is widely known to be unreliable in shedding the right amount of load. Thus, to improve its performance, new UFLS schemes which are referred as adaptive and intelligent have been proposed. In an adaptive UFLS scheme, the amount of load to be shed is determined based on the estimated magnitude of disturbance (power imbalance). The magnitude is normally estimated using the *Swing Equation* which requires an estimated value of the rate of change of frequency (df/dt) in the system [9]. The load mismatch between generated power and load power can be calculated using the *Swing Equation* [10]. The inertia constant H can be calculated as the total kinetic energy divided by the system base power.

$$\frac{2H}{f_0}\frac{df}{dt} = P_m - P_e = P_{diff}$$

6.3. Methodology & control strategy of the power management system

On August 1, 2021, the grid logs provided by the industrial partner registered the failure of five generators as shown in the figure below.

Figure 7: Grid failure on August 1, 2021

The following tables include information useful for performing the analysis of the power disturbances.

Table 4: Faults identified in the grid logs on August 1, 2021

	Date	Time	Controller	Pwr	Gfrq	Bfrq	Reason	Ig1	Ig2	Ig3
198	44409	16:59:59.3	C01 - SGB 1603	506.0	49.9	49.9	BOC IDMT	1047.0	975.0	1042.0
183	44409	17:00:00.9	C03 - SGC 1618	724.0	49.6	49.6	BOC IDMT	1459.0	1392.0	1322.0
172	44409	17:00:05.8	C06 - SGB 1601	566.0	45.4	45.4	BOC ShortCurr	1754.0	1729.0	1738.0
163	44409	17:00:06.4	C04 - SGC 1615	737.0	43.9	43.9	BOC ShortCurr	2132.0	2070.0	2029.0
150	44409	17:00:07.6	C05 - SGP 1309	225.0	48.1	40.6	Stp GCB fail	0.0	0.0	0.0

When the failure of generator C01 (event 1) occurs at 16:59:59.3 pm, the power generation lost amounts to 506 kW.

Table 5: Specification of the generators[5]

ΔP_e event 1 (Generation power lost)	506 kW
Generators running during first event	5
ΔP_e event 2 (Generation power lost)	724 kW
Generators running during second event	4
Generator base power	800 kVA
Generator rated frequency	50 Hz
Generator rated voltage	415 V

[5] As per the generator samples shared by the industrial partner

To mitigate the impact of generator CO1's trip and all other power faults thereafter, *DMSystem Controller* is proposed. The controller leverages the data analytics strength of Python and related libraries, takes as input the datasets provided by the industrial partner and outputs load shedding commands to be sent to the loads' circuit breakers with the end goal of preventing blackouts.

The step-by-step control procedure that generates load shedding commands from available grid data is outlined as follows.

Initially, the controller scans each ComAp grid log entry as data is being stored in search of generator failure alarms (BOC IDMT, BOC ShortCurr, Stp GCB fail, Sd)[6]. The ComAp Reference Guide refers to *BOC ShortCurr* as an overcurrent protection; *BOC IDMT* as current/voltage unbalance, active power, short current and earth fault current protection; *Stp GCB fail* as alarm in the absence of feedback response to a change of the control output and *Sd* as shutdown in the event of generator voltages exceeding the protection limits. Once a failure is detected, the controller calculates the load mismatch and follows the defined load shedding strategy in

Table 6 to propose the amount of loads to disconnect. Figure 8 details the power availability assessment made by *DMSystem Controller* and its recommendation to disconnect a total of 506 kW load power.

Table 6: DMSystem Controller Load Shedding Strategy

Load Shedding Strategy
1.- Identify the fault occurrences based on the failure alarms
2.- Sum the power generated by the active generators prior to the fault
3.- Sum the power generated after the fault
4.- Assume the power needed by the loads equals to the power generated prior to the fault
5.- Subtract the power generated after the fault from the power needed to meet the load demand
6.- Determine by how much the total load power should be reduced
7.- Determine which loads should be disconnected
8.- Send the appropriate load shedding commands

[6] These failure alarms are identified in the ComAp Reference Guide

```
--------------------------------------------Fault 1 ---------------------------------------------
The index of the fault is 198 on date 44409 at time 16:59:59.3 occuring at controller C01 - SGB 1603

Power generated at the instant of the fault is 506.0 kW

The index of the last power value printed by Controller 1 is:  199
Last power registered by controller 1 is 0.0 kW

The index of the last power value printed by Controller 2 is:  203
Last power registered by controller 2 is 490.0 kW

The index of the last power value printed by Controller 3 is:  200
Last power registered by controller 3 is 323.0 kW

The index of the last power value printed by Controller 4 is:  201
Last power registered by controller 4 is 536.0 kW

The index of the last power value printed by Controller 5 is:  202
Last power registered by controller 5 is 429.0 kW
Last power registered by controller 6 is 0 kW
Last power registered by controller 7 is 0 kW

The power generated prior to Fault 1 amounts to 1778.0 kW
The power generated right after Fault 1 amounts to 1272.0 kW
The total load power that should be disconnected is 506.0 kW
```

Figure 8: Assessment of the power imbalance made by the controller

```
--------LOADS----------------

The active load groups with their rated power [kW] and in the disconnection priority order
Tunnel Feeder        50
Secondary 1        1653
Secondary 2         234
Camp & Worshop      400
Primary 2           434
Primary 1           362
Primary 3           419
```

Figure 9: Active loads (peak consumption) in the grid

In the fourth statement of the Load Shedding Strategy as reported in Table 6, it is assumed that the grid maintains its electrical balance prior to any detected fault i.e., power generated equals load demand. However, in the current case study, the total power generated prior to fault 1 amounts to 1778 kW (Figure 8) whereas the sum of the loads' rated power (peak consumption) reaches 3552 kW (Figure 9). This mismatch would have created an inherent power imbalance in the grid. Since the dataset provided by the industrial partner lacks load-related data, a correction factor ($ß = \frac{total\ power\ generated}{sum\ of\ loads'rated\ power}$) has been multiplied to each load group's rated power such that the simulated grid remains balanced in the absence of faults. The updated power consumption of the different load groups is reported in the figure below.

```
The correction factor beta = 1778.0 / 3552 = 0.5005630630630631

The updated load power consumption [kW] and in the disconnection priority order
Tunnel Feeder Updated       25.028153
Secondary 1 Updated        827.430743
Secondary 2 Updated        117.131757
Camp & Worshop Updated     200.225225
Primary 2 Updated          217.244369
Primary 1 Updated          181.203829
Primary 3 Updated          209.735923
```

Figure 10: Active loads (updated consumption) in the grid

Based on the disconnection priority defined by the industrial partner and reported in Table 1 and Figure 10, a load shedding scheme (Table 6: DMSystem Controller Load Shedding Strategy) has been established to cope with the power generation shortage.

Accordingly, the *DMSystem Controller* has proposed to disconnect the first 2 load groups (Tunnel Feeder & Secondary 1) whose cumulative rated power amounts to 852.46 kW. It is worth highlighting that, since the load groups consume a discrete power value, the proposed controller cannot always shed the exact amount of power in excess. For instance, in the case of Fault 1, the controller recommends the shedding of 506 kW; however, 852.46 kW will be effectively disconnected as shown in

```
--------DISCONNECTION----------------
The quantity of load group to be disconnected is 2 i.e [25.028153153153156, 827.4307432432432]
The disconnected power is 852.4588963963964 kW

The status of the 7 load groups before Fault 1
Status1    1
Status2    1
Status3    1
Status4    1
Status5    1
Status6    1
Status7    1
```

Figure 11: Assessment of the load groups to be disconnected.


```
--------DISCONNECTION----------------
The quantity of load group to be disconnected is 2 i.e [25.028153153153156, 827.4307432432432]
The disconnected power is 852.4588963963964 kW

The status of the 7 load groups before Fault 1
Status1    1
Status2    1
Status3    1
Status4    1
Status5    1
Status6    1
Status7    1
```


Figure 11: Assessment of the load groups to be disconnected

The resulting set of commands to be transmitted to the circuit breakers appears in Figure 12. A circuit breaker receiving 1 as its command will stay closed whereas the command 0 mandates the opening of the circuit breaker. The loads attached to an opened circuit breaker are disconnected from the grid.

```
The set of commands to be sent to the circuit breakers
Status1    0
Status2    0
Status3    1
Status4    1
Status5    1
Status6    1
Status7    1
```

Figure 12: Disconnection commands sent to the circuit breakers

A suitable communication network (see next chapter on Communication Network) will enable these commands to reach the circuit breakers on the load side within 10 milliseconds. Subsequently, the circuit breakers will disconnect both Tunnel Feeder and Secondary 1 from the grid. The shedding of these load groups is expected to regularize the operation of the plant and prevent the failure of generator C03 at 17:00:00.9 pm (1.6 seconds after the failure of generator C01) as shown in Table 4 if no action is taken. Once the controller accurately detects and deals with fault 1, the additional faults shown in the table will be avoided. Furthermore, a simplified replica of the grid has been designed and simulated in MATLAB/Simulink to showcase the effectiveness of the proposed control scheme.

6.4. Analysis of a power disturbance and modelling of system frequency response

To analyze the system frequency response due to the power disturbance, and validate the action of the load management system, a circuit was designed in Simulink consisting of generation, distribution, and load consumption sections. The following design choices have been considered:

1. The generators are modeled using a Synchronous Machine (SM) block that considers the inertia of the rotor. The mechanical input to the SM is provided by a Droop Governor, which also provides Primary Frequency Control in case of a power disturbance. The voltage control is done by a Voltage Regulator and Exciter model, which outputs a field voltage to the SM.
2. Secondary Frequency Control is modelled using an Integral Controller.
3. Three phase series RL loads are used with a Power Factor of 0.7.
4. Two generators are simulated in the system. A first one that is suddenly removed from the system to simulate a power disturbance, and a second one with a combined inertia constant that simulates the response from the rest of generation units.
5. Two loads are considered in the system. A first one which is the load to be shed when a fault occurs, and the second one which represents the remaining loads.

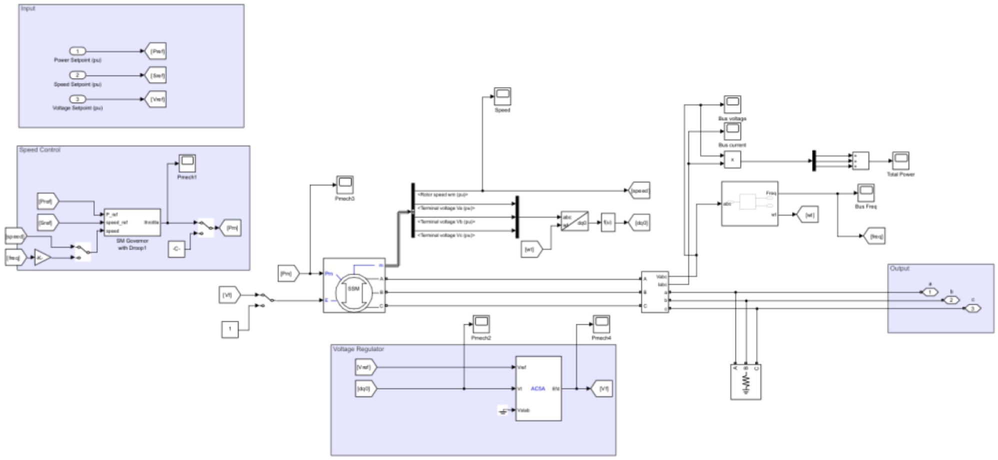

Figure 13: Synchronous Generator model

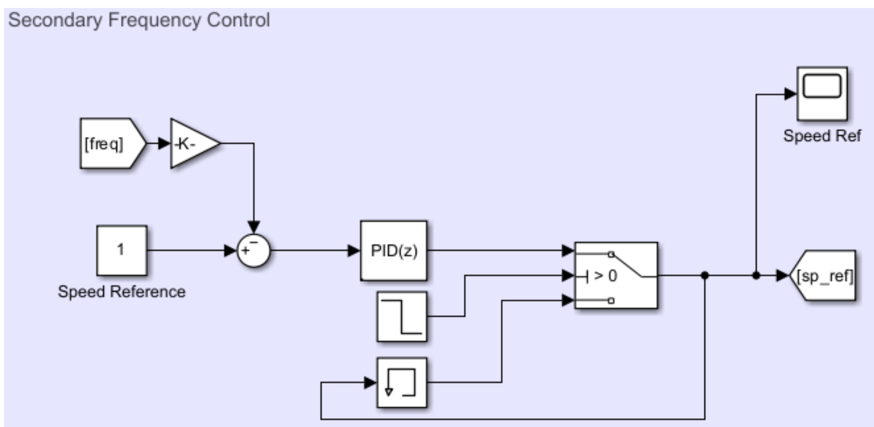

Figure 14: Secondary Frequency Control

To estimate the system parameters required to perform the simulation (inertia of the system, time constant of governor), an offline inertia estimation procedure has been carried out.

The following two plots show the system frequency response and the rate of change of frequency df/dt (ROCOF) during a power disturbance event where two generators fail consecutively, as presented in the data provided by the industrial partner.

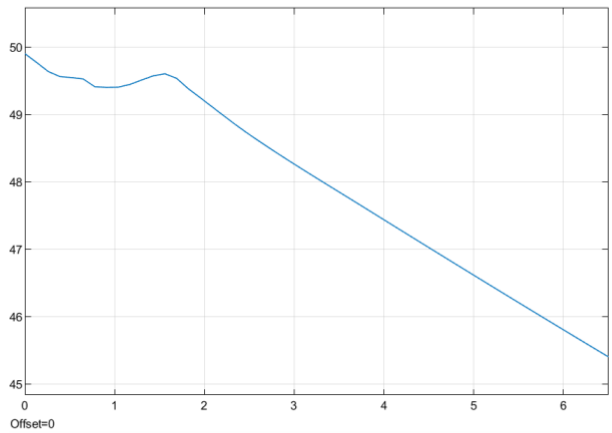

Figure 15: System frequency response during power disturbance

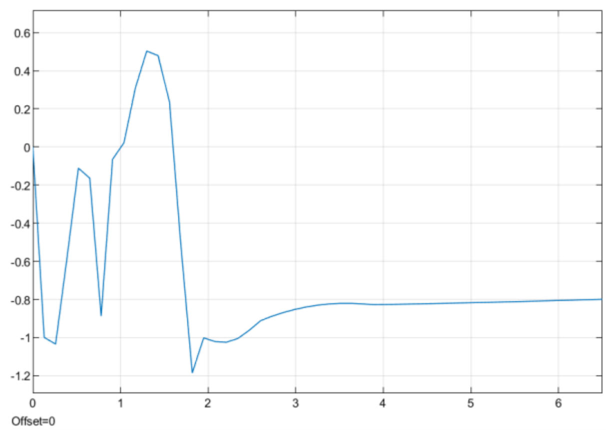

Figure 16: Calculated rate of change of frequency df/dt (ROCOF) from system frequency response

In offline inertia estimation, the data captured just after the contingency, or a large disturbance is used to estimate the inertia after the event. This is also known as a post-mortem analysis. If mechanical power is assumed constant and damping is neglected, then inertia estimates can be obtained as:

$$H_{Total} = \frac{1}{2S_r} * \frac{-\Delta P_e}{\frac{d\left(\frac{\Delta f}{f_r}\right)}{dt}}$$

Where ΔP_e is the electrical power change, S_r is the rated apparent power and f_r is rated frequency [4].

From the experimental data, it is known that the active power imbalance of the first event is 506 kW. Also, the minimum ROCOF observed in the plot during the first event can be rounded to -1. If we assume that all generators are rated at 800 kVA, then the total base power is 4,000 kVA and the total Inertia becomes:

$$H_{Total} = \frac{1}{2\ (4000\ kVA)} * \frac{-506\ KW}{-\frac{1\frac{Hz}{s}}{50\ Hz}} = 3.16\ s$$

The total inertia per unit is estimated to be 3.1625 seconds and thus the inertia of each generator is estimated as 0.63 seconds.

Using the said figures with an appropriate value of time constant for the Droop Governor, the model was completed. The next plot shows system frequency response when trying to replicate the power disturbance from the experimental data.

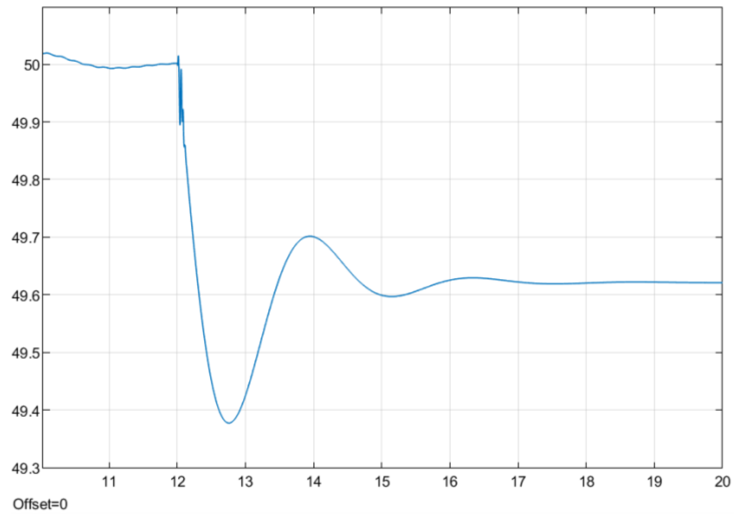

Figure 17: System Frequency response during power disturbance simulated in Simulink

6.5. Validation of the Load Shedding Strategy

If we input the results from the Load Shedding Strategy discussed in the chapter Methodology & control strategy of the power management system into the Simulink model, a comparison between the Load Shedding and base scenario can be made.

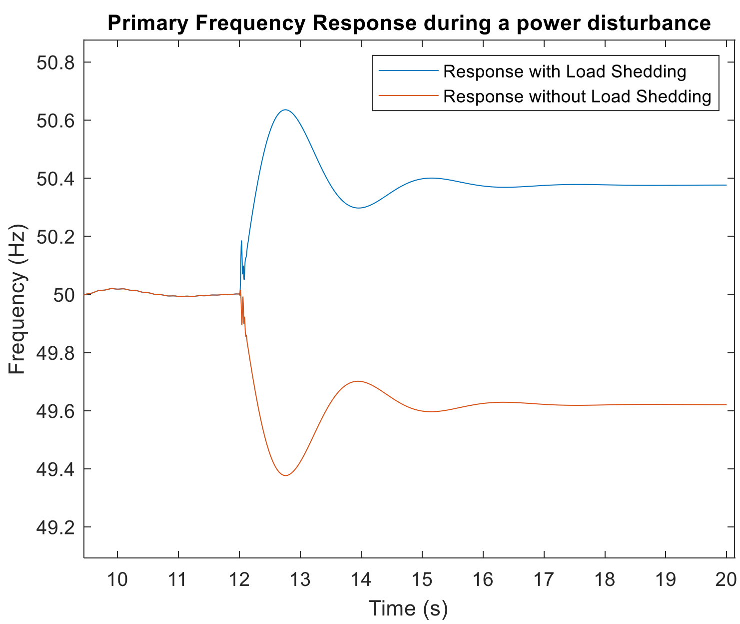

Figure 18: Validation of the Load Shedding Strategy

The following can be concluded from the figure:

1. Without Load-Shedding, the system frequency decreases (orange line). This requires Primary Reserve to stabilize the frequency. In an isolated system, there might not be enough primary reserve to correct the frequency deviation, which can lead to blackouts.
2. With Fast Load-Shedding, the system frequency increases (blue line) because the load shed in this case is higher than the generation capacity lost. The dynamic frequency deviation remained below 800 mHz, and the system can correct the quasi-steady-state frequency deviation later.

The results of the microgrid investigation are included in a dashboard (available in Appendix C or on YouTube) to explicitly highlight the main findings and allow for a prompt understanding of the control strategies involved.

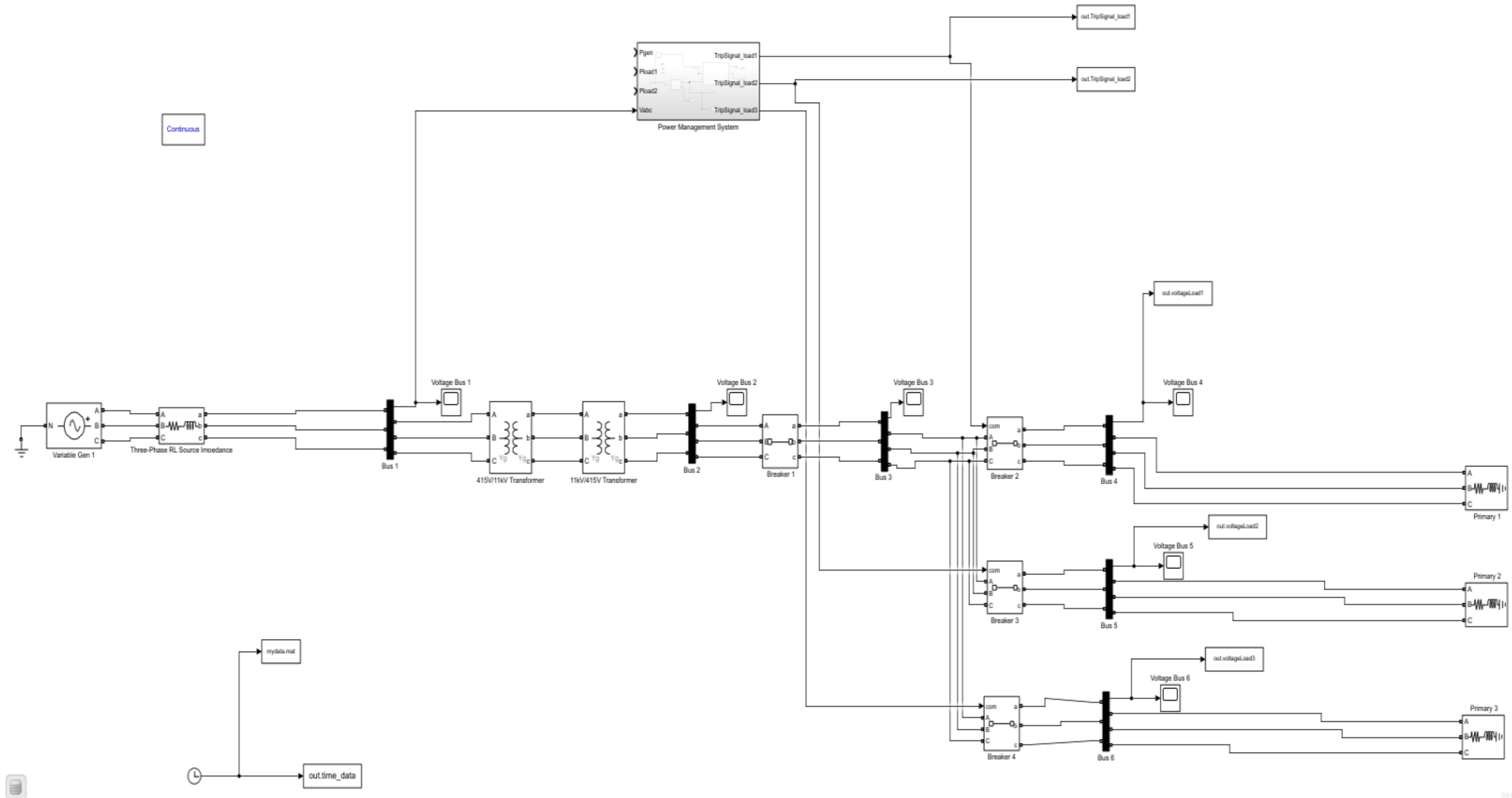

Figure 19: Simulink model of the investigated grid

7. Communication Network

The proposed design of the communication network is presented in Figure 20. Although the implementation of the network design is a crucial part of the proposed solution, the scope for this project includes only an overview of the network excluding details of the underlying technologies.

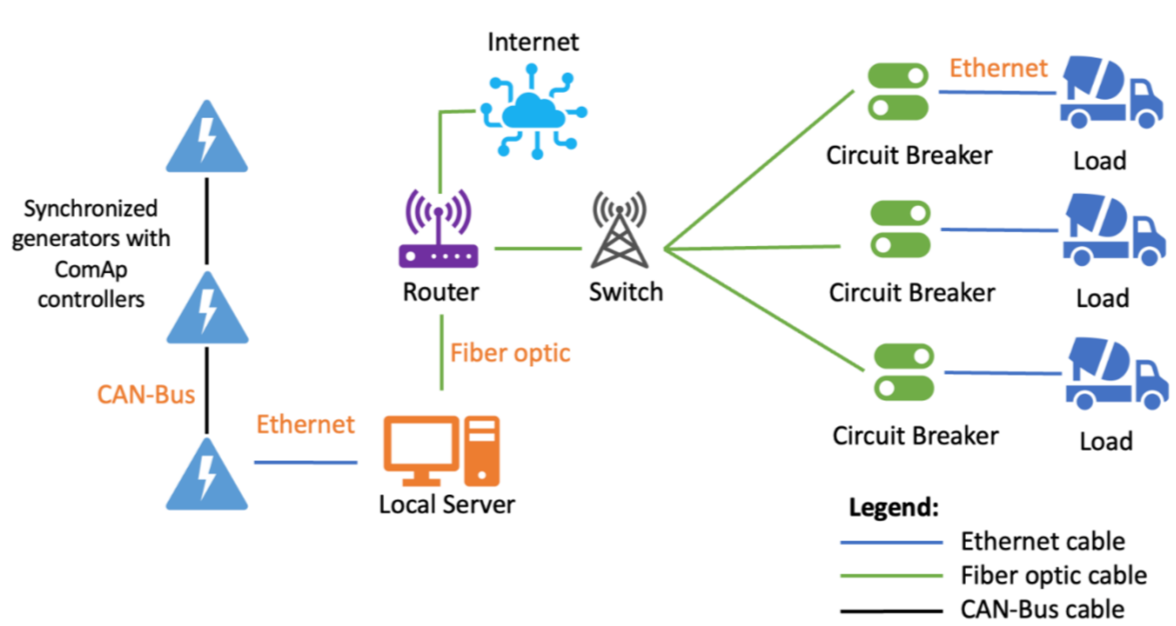

Figure 20: Detailed layout of the proposed communication network

One of the main components of this network is the local Personal Computer (PC) which acts as the local server. The ComAp controllers send all information related to the five generators connected to the grid to this server. In addition, the *DMSystem Controller* also runs on the server to detect grid failures and dispatch appropriate load shedding commands. The design choices and equipment specifications presented below have been adjusted to adhere to the communication guide of the ComAp controllers installed onsite.

An Ethernet cable is used to connect the ComAp controllers to the local server as recommended by the ComAp communication guide mentioned in Figure 21. However, to tackle the issue of speed and length which are limited to 100 meters and 100 Mbps respectively, the Ethernet cable can be connected to a fiber optic cable using the fiber optics to Ethernet converter. This technology enables the Ethernet network to be extended up to 2 and 100 kilometers for multimode and single-mode fiber optics respectively [12]. In terms of data communication with the ComAp controllers, Modbus TCP/IP (Transmission Control Protocol/Internet Protocol) is chosen over Modbus RTU (Remote Terminal Unit), considering that the former enables an easier connection with the Ethernet cable, easier to troubleshoot, and has a higher response time. A more detailed comparison between them is presented in Table 7. Additionally, this local server will also run the SCADA as the system is remotely controlled.

The load shedding commands originating from the *DMSystem Controller* located on the local server transit to the router using a fiber optic cable. Despite being costly, fiber optic is a reliable transmission medium that could cover great lengths of up to 50 to 100 kilometers with a maximum communication rate between 1 to 10 Gbps. Besides connecting the local network to the internet, the router also functions as a security layer (e.g., firewall) protecting the network against intrusion.

Recommended communication cables for ComAp controllers				
Interface	**Cable**	**Connector**	**Max. Length**	**Max. Comm. Rate**
RS232	Serial cross-wired cable standard Null-modem cable	DB 9	10 m	57.6 kBd
		DB 9	10 m	
RS485	Shield twisted pair[1]	NONE	1000 m	57.6 kBd
Ethernet	STP or UTP cable	RJ45	100 m	10/100 Mbps
USB	Standard USB A-B cable	USB A-USB B	5 m	115200 Bd
CAN	Shield twisted pair[2]	NONE	200/900 m*	250/50 kBd*

Figure 21: Recommended communication cables for ComAp controllers based on its communication guide

Table 7: Comparison between Modbus RTU and Modbus TCP/IP [13] [14]

Modbus RTU	Modbus TCP/IP
Runs on a serial-level protocol	Runs on Ethernet, which makes it easier to troubleshoot but might make the communication rate faster than needed
Simpler, efficient wiring, cheaper	Simpler to implement in devices with TCP/IP socket
Can be daisy-chained with all devices	Needs to involve expensive switches
Can only have one master – additional masters would destroy the communication network	Not limited to one polling device
Response time depends on the communication speed. The detail is not shorter than the time needed to send/receive 3 and a half characters (based on the communication guide)	Typical response time: 25 milliseconds (based on the communication guide)

After being sent to the internet, a network switch allows the circuit breakers with their individual communication ports to be connected to the fiber-optic-based section of the network and actuate the transmitted disconnection commands. The said commands will dictate whether a circuit breaker should open or remain close. As detailed in

Table 1, 7 load groups with distinct rated power and circuit breaker connect to the plant, contrasting with the 3-load network depicted in Figure 20. Besides the main components mentioned before, the communication network may include other accessories such as connectors, couplers, splices, multiplexing devices, and amplifiers.

Throughout the fiber optic network spanning from the local server to the circuit breakers, TCP/IP is involved. This protocol has been used to transmit data from the simulation to the real world and receive it back without loss of data. The interaction between two servers (or computers) across the network is of the "client-server" kind, in which a client requests and receives a service from another server or computer on the network. The initial communication is reassembled into packets by the Transmission Control Protocol (TCP) layer. The Internet Protocol (IP) then addresses all elements of each data packet's address to ensure that it reaches its intended destination. Each IP gateway server or computer on the network examines this Internet Protocol address to determine where it should be forwarded. The TCP/IP batch represents a chain of protocol layers for networks and systems, allowing transmission between any sort of device. The prototype is made up of five distinct, yet complementary layers, as shown in Figure 22 [15].

User Application Programs

Application Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer

Network Link(s)

Figure 22: The five layers of TCP/IP [15]

Furthermore, TCP/IP has been used in previous works serving similar purposes as this demand management system. In [15], TCP/IP is integrated with smart meters within a distribution network, and [16] employed the protocol in the microgrids typology of an intelligent load management system. The latter also displays a total processing time of 10 milliseconds for the data to be transmitted from server to client and ultimately to circuit breakers. This result is significant since the system under consideration also aims to achieve a response time of under 10 milliseconds.

In this study, a server-client communication network based on TCP/IP protocol is designed using MATLAB/Simulink to showcase that the load shedding commands can reach the circuit breakers and disconnect the appropriate load groups within 10 milliseconds.

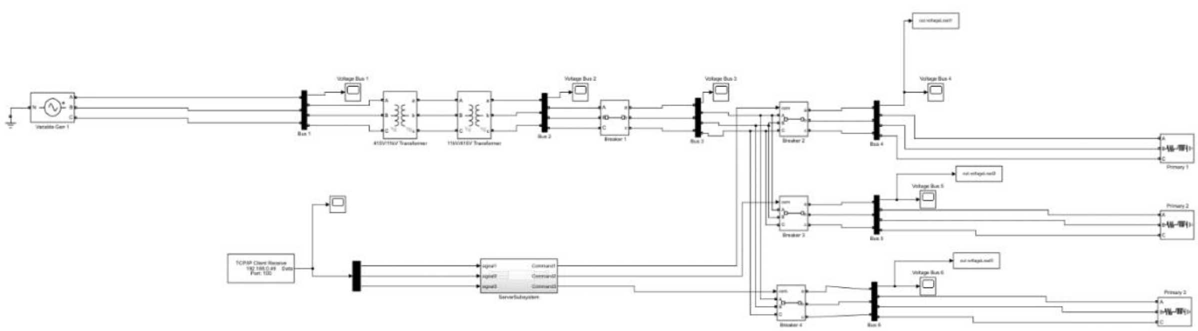

Figure 23: Scheme of the communication network

The communication network modelled in Figure 23 comprises a generator to which three load groups with their specific circuit breakers are connected. The command signals for the circuit breakers originate from a remote server and are transmitted through TCP/IP protocol as follows.

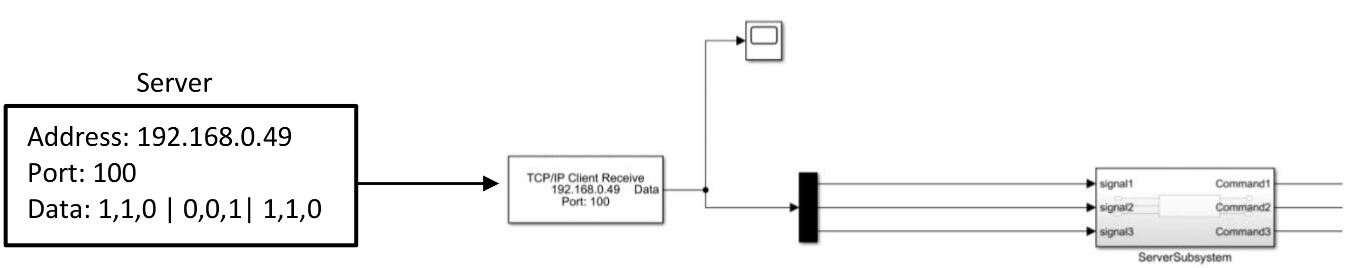

Figure 24: Server-Client data transmission

The 10-second simulation proposes the transmission of 3 sets of commands from the server to the client and then to the circuit breakers. At the beginning of the simulation, commands 1, 1, 0 are sent, meaning that the first and second load groups will remain connected whereas the third load group should be disconnected from the grid. At simulation time t = 4 seconds, the commands become 0, 0, 1 and change to 1, 1, 0 at t = 8 seconds. It is important to highlight that at t = 0, 4, and 8 seconds, the Simulink simulation will wait for full and successful transmission of the sever data before proceeding. This characteristic allows observation of the impact of the commands received on the behavior of the load groups and assess the data processing time from server to client to circuit breakers.

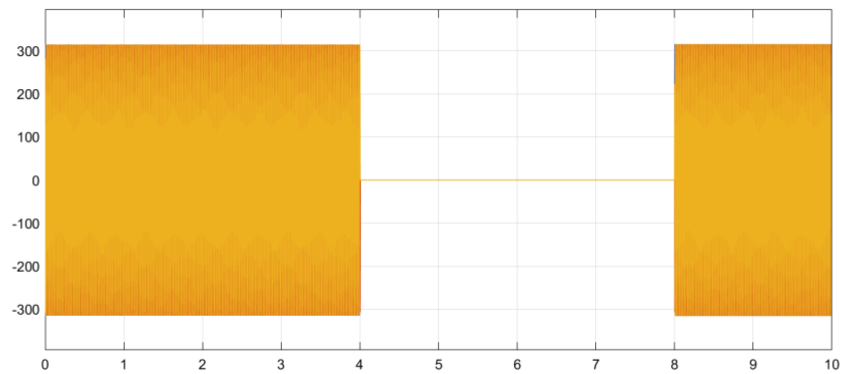

Figure 25: Voltage response of load group 1. Commands received [t=0s: 1, t=4s:0, t=8s:1]

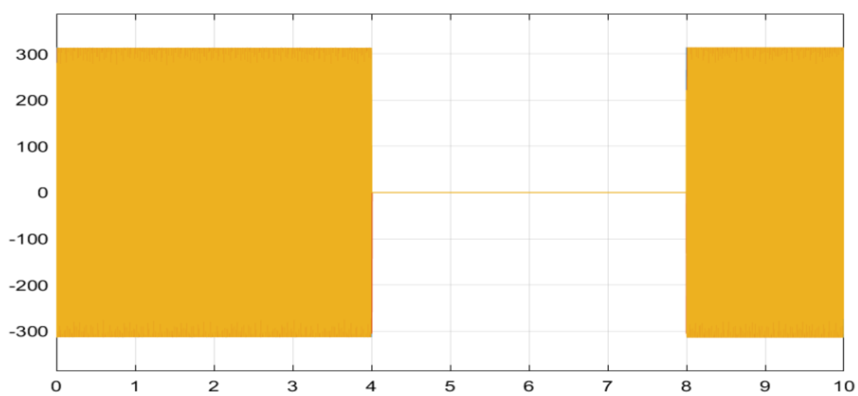

Figure 26: Voltage response of load group 2. Commands received [t=0s: 1, t=4s:0, t=8s:1]

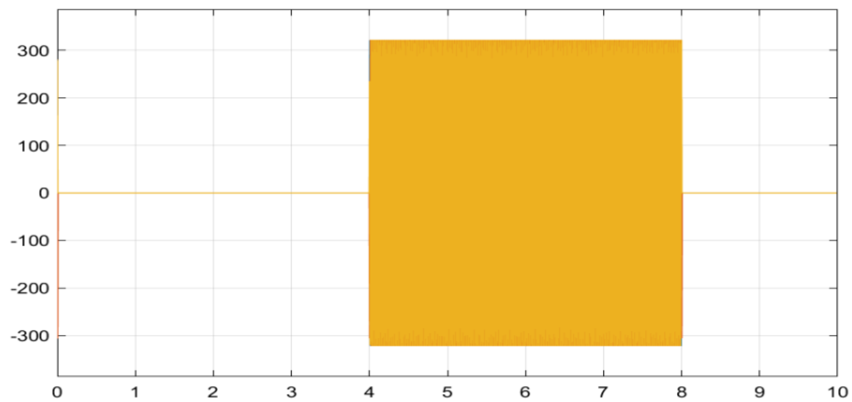

Figure 27: Voltage response of load group 3. Commands received [t=0s: 0, t=4s:1, t=8s:0]

A closer look at the voltage response of load group 2 around t = 4 seconds when the circuit breaker receives the command 0 to disconnect the load group from the grid reveals that the response time of the command signal falls below 10 milliseconds Figure 28. With a disconnection command sent at t = 4 seconds, the circuit breaker effectively disconnects load group 2 at t = 4.007 seconds (response time of 7 milliseconds). In other words, the time taken for the data to be transmitted from the local server to the circuit breaker is achieved under the system's constraint of 10 milliseconds. **This response time (under the same simulation setup) seems to be machine independent as several PCs with different computing power and connected to different internet networks reach similar response time (see Appendix E)**.

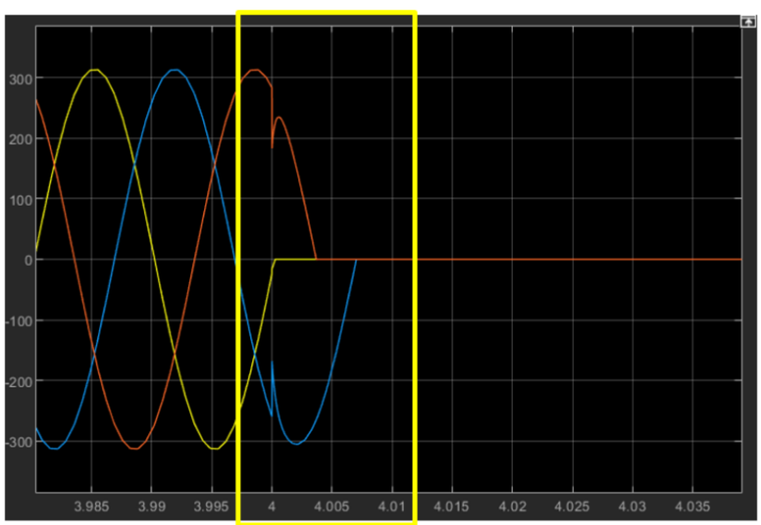

Figure 28: MATLAB and Simulink simulation results show the response time is achieved in under 10 milliseconds

In the simulation setup, the server runs on the local PC (Figure 20) i.e., on the power generation site which is located at 1.5 km from the circuit breakers and the load groups. Figure 29 summarizing the simulation parameters shows that the data size (number of data entries to be processed at each simulation step) is set to 3; thus, an array of 3 integer values e.g. [1, 0, 1] constitutes the data and indicates its required length at each simulation step. Furthermore, by enabling blocking mode (Figure 29), the simulation awaits to receive an updated array of 3 disconnection commands before proceeding to the next time step. The timeout of 0.1 second defines the duration of the simulation's waiting period; in case there is no data to process within that timeframe, the output becomes null (0). The block sampling time of 4 seconds governs the execution rate of the TCP/IP receive block in Simulink[7].

Regarding data rate of Ethernet, the local network hosting the simulation setup presents a maximum possible data transfer rate of 130 Mbps (Figure 30). Theoretically, this transfer rate can only be reached in the absence of network congestion and over relatively short distances with no or almost no delays (latency). Considering that the data type *int8* (Figure 29) encapsulates each disconnection command in 8 bits of storage, 130 Mbps can be seen as a fast network connection.

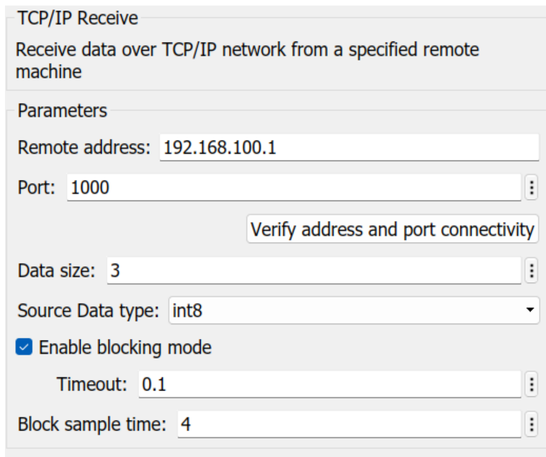

Figure 29: Simulation parameters for the TCP/IP network communication simulation

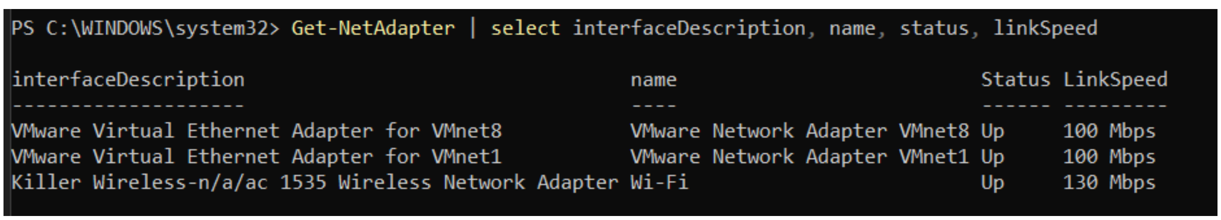

Figure 30: Data rate of Ethernet on simulation PC

Since the load shedding commands can reach the circuit breakers within the required timeframe of 10 milliseconds, the proposed *DMSystem Controller* can successfully help mitigate the consequences of power imbalance in the grid. Nevertheless, it is also important to pay attention to the caveat that this simulation does not consider the physical constraints of the components which might add delays, thus requiring a longer response time.

The phenomenon of delay, or latency, occurs in all transmission media. Latency in optical fibers is determined by the refractive index of the optical fiber and is relatively constant at a given optical wavelength. However, latency cannot be eliminated; it can only be managed. In optical network applications where latency can be detrimental, active network equipment, optical transceivers, optical cable, and even optical cable routing must all be carefully examined. Selecting an optical cable with the lowest index of refraction for the wavelength of interest reduces delay. Using the shortest optical fiber possible while routing can also help to reduce latency [17].

[7] https://www.mathworks.com/help/instrument/tcpipreceive.html

8. Financial, socio-economic, and environmental analysis

The following section details the financial analysis as well as the social and environmental impact of the fast-response demand-management system.

8.1. Financial analysis

The financial analysis consists of preliminary calculations of total capital expenditure (CAPEX) and operational expenditure (OPEX) for the proposed system. The CAPEX includes the control system and communication network. Two cases are investigated – the chosen fiber optic communication network and Ethernet communication network. The table below shows the total CAPEX of the proposed system, including components, units, price per unit and total price. All the unit prices are estimates based on average values found online.

Table 8: CAPEX breakdown of system with fiber optic communication network

Component	Subcomponent	Unit	Unit price (€)	No. of units	Total price (€)
Control system	Raspberry PI 4B (8 GB)	Piece	72.00[8]	1	72.00
	Voltage sensor	Piece	50.00	16	800.00
	Current transformer	Piece	40.00	16	640.00
	Subtotal				**1,512.00**
Fiber optic communication network	Cabling & installation[9]	Meters	36.00	1,500	54,000.00
	Wi-Fi router	Piece	550.00	1	550.00
	Local PC	Piece	2,000.00	1	2,000.00
	Subtotal				**56,550.00**
TOTAL					**58,062.00**

As can be observed from the CAPEX, the total price mainly consists of investment into the fiber optic communication network, which accounts for 97% of the total costs. The communication network is an example of critical infrastructure, as it enables the realization of the 10 millisecond response time target and ensures reliability of the whole system. However, given that cost-effectiveness is a significant reason behind the introduction of this load shedding system, the solution may appear less attractive. Therefore, it is recommended that fiber optic is used in the communication network for the entire plant, not only the proposed load shedding system. This will reduce the payback time of the communication network as it is now a part of total business revenue, while ensuring more reliable, faster, and safer communication, which is especially relevant in remote locations, susceptible to extreme weather conditions.

The CAPEX for the alternative solution that represents an Ethernet communication network is calculated and presented in the table below.

[8] https://www.raspberrypi.com/products/raspberry-pi-4-model-b/

[9] https://dgtlinfra.com/fiber-optic-network-construction-process-costs/#:~:text=How%20Much%20Does%20it%20Cost,or%20bury%20fiber%20optic%20cable.

Table 9: CAPEX breakdown of system with Ethernet communication network

Component	Subcomponent	Unit	Unit price (€)	No. of units	Total price (€)
Control system	Raspberry PI 4B (8 GB)	Piece	72.00	1	72.00
	Voltage sensor	Piece	50.00	16	800.00
	Current transformer	Piece	40.00	16	640.00
	Subtotal				**1,512.00**
Ethernet communication network	Cabling & installation	Meters	7.00	1,500	10,500.00
	Ethernet switch	Piece	50.00	15	750.00
	Wi-Fi router	Piece	550.00	1	550.00
	Local PC	Piece	2,000.00	1	2,000.00
	Subtotal				**13,800.00**
TOTAL					**15,312.00**

In this case, the communication network still accounts for 90% of CAPEX even though the total CAPEX is 4 times lower than with a fiber optic communication network. However, the essential system features such as reliability and fast response time might not be achieved. Ethernet communication is typically only suitable for distances less than 100 meters. Switches can be added to increase the range at every 100 meter intervals, but this deteriorates signal quality and network speed. Therefore, it is clear that the financial gains with an Ethernet communication network are unable to justify the accompanied decline in system performance.

In addition to the CAPEX, the OPEX of the proposed solution with the fiber optic communication is compared with an alternative of adding diesel generator redundancy. The cost of hardware components in the expenditure analysis are based on average market values. The OPEX represents the total operational cost of the system calculated on a monthly basis. Since the proposed solution in this project is an automated demand management strategy, no dedicated human resources are needed to oversee the system. The total OPEX per month is shown in Table 10.

Table 10: OPEX of the load shedding system

Component	Unit	Unit price (€)	No. of units	Total price (€)
Standard energy management platform	Monthly subscription	300.00	1	300.00
Cloud subscription (2 TB of Google Drive)	Monthly subscription	8.33	1	8.33
Internet service provider (500 Mbps)	Monthly subscription	775.00	1	775.00
Total				**1,083.33**

Financial comparison of alternative solutions – adding diesel generator redundancy

There are two main alternative solutions to overcome the issue of unexpected power outages. The first is to include redundant diesel generators that can take on the load if a running unit fails. The second is to incorporate energy storage that can inject lost power. However, given that the cost of battery solutions is significantly more expensive, it is clearly not economically feasible.

It is more typical to rent diesel generators in industry than purchase new ones. The OPEX considers only the monthly rental cost of these units which also includes cost of maintenance. It can be assumed that there is no net change in fuel consumption by increasing redundant generators as the fuel consumed will only consist of the fuel initially allocated to the units that failed.

The overall capacity of the diesel generators on-site is governed by the peak load. According to

Table 1, the sum of the rated power of the load types is around 3,550 kW. This is the ideal power consumed by the loads according to the equipment manufacturers. However, a more realistic number is the measured peak load which in this case is 3,200 kW. This value will be used to size the capacity of diesel generators.

Assuming that the capacity of the diesel generators will be 20% higher than the measured peak load, with a power factor of 0.8, the apparent power of diesel generator on-site would be:

$$Apparent\ power = \frac{1.2\ \times\ Measured\ peak\ load}{Power\ factor} = \frac{1.2\ \times\ 3{,}200}{0.8} = 4{,}800\ kVA \qquad (3)$$

The choice of diesel generators used in industry is primarily influenced by fuel efficiency. The most commonly used units in similar industrial applications are 300 kVA and 650 kVA[10] engines. A combination of these are used to obtain the desired capacity of 4,800 kVA as shown in Table 11.

Table 11: Assumed configuration of diesel generators on-site

Apparent power of diesel generator (kVA)	No. of units	Total apparent power (kVA)
650	6	3,900
300	3	900
Total		**4,800**

The assumed redundancy capacity is set at 20% of total capacity. This can be composed of a 650 kVA and a 300 kVA generator to obtain the desired 960 kVA. The corresponding OPEX is shown in Table 12.

Table 12: Increase in equipment cost due to added diesel generator redundancy

Component	Unit	Unit price (€)	No. of units	Total price (€)
Diesel Generator 650 kVA	rent/month	4,000.00	1	4,000.00
Diesel Generator 300 kVA	rent/month	2,600.00	1	2,600.00
Total				**6,600.00**

It is clear from Table 10 and Table 12 that the demand management system is around €5,500 cheaper than the alternative solution of adding diesel generator redundancy. That, however, is to compare only the OPEX of both systems. Adding diesel generators to the system promotes increased usage of fossil fuels and potentially increases carbon dioxide emissions of the whole system. Moreover, it contributes to the aggregation of secondary emissions during the production lifecycle of generators. If new diesel generators are to be purchased to add redundancy, this would be a poor usage of capital as the assets would not be regularly in use. In all cases, the proposed solution with a fiber optic communication network incorporated into the entire plant is a more advisable investment in the long run.

[10] https://www.cummins.com/en/in/generators/500-1010-kva-diesel-generators

8.2. Social and environmental impact

Monetary savings from this solution can be used in various ways, such as raising the salaries of employees or on research and development. Both can potentially help local communities and the planet, as research and development can be focused on sustainability of the industry and improvements to energy security.

The finalized demand management system can be used in a multitude of other applications. These include hospitals in remote locations with limited access to the electricity grid and are more prone to power shortages. Even though hospitals tend to have a back-up power system in place for safety, it is still possible to have power shortages if the back-up fails. This can especially be a problem in countries with an unstable electricity supply. A demand management system can help to disconnect loads that are less vital, allowing uninterrupted supply to the most vital loads – patients in intensive care, emergency care, operating rooms, elevators etc. When it comes to patients in emergency care, the time response of the system is vital, as treating those with diseases such as strokes or heart failures require a time response of seconds. The same can be said about patients in intensive care, especially those needing ventilation.

A related case study in Venezuela presents a perfect example of the applicability of a demand management system. A widespread power outage coupled with the partial failure of the back-up generators in some hospitals caused the death of 26 patients [7]. An unstable electricity grid is a common, yet serious problem in most developing countries especially in Africa so this load management system can be a critical solution to save lives.

Moreover, financial resources saved due to the implementation of this solution can be reallocated to improving infrastructure or investing in education in developing countries. The latter implies that a community, for example, can focus on investing money to create apprenticeships for high school and college-level students. Reliability of power impacts social welfare and overall quality of life. The use of this demand management system can allow members of the host community to no longer have to adapt their lifestyles according to the availability of power. Enhanced awareness in concepts related to energy efficiency could foster a culture where agents are encouraged to install more energy efficient equipment to reduce the likelihood of switching off loads.

Environmental impact is an additional benefit of our proposed system, as it reduces the need for added redundancy in terms of power generation infrastructure such as diesel generators and additional solar capacity. The control system that allows to proactively disconnect loads based on their priority can reduce the total carbon emissions that result from the burning of diesel in the generators. The diminished need for redundancy could also help reduce the overall size of the power generation system which would alleviate pressure on the carbon footprint, as the requirement of less diesel generators on site would cut down secondary emissions due to the transportation of parts required in its manufacturing process, as well as emissions created during the manufacturing process itself.

9. Conclusion

The primary objective of this project involves the design of a fast-response demand-management system capable of coping with unexpected reductions in power generation availability to ensure reliability and guard against unexpected power outages. Throughout the investigation, it has been demonstrated that the proposed solution *DMSystems* considers all stakeholder expectations and can deliver on the technical requirement of responding to an electrical fault – observed through a reduction in grid frequency below the desired threshold – within the desired roundtrip response time of 10 milliseconds. The modelling of the electrical system including the generation, distribution, control, and load units follows the guidelines provided by the industrial partner and behaves as expected upon simulation i.e., *DMSystems* disconnects the load group(s) with the lowest priority as soon as a power imbalance is detected in the grid. The fundamental utility of this system lies in its ability to delay the onset of imminent blackouts to the entire plant due to the loss of power generation, by disconnecting low priority load groups to maintain system frequency. In this way, the loads critical to the functionality of the plant can continue to operate until the lost power generation infrastructure is restored.

Although the financial analysis concludes that the fiber optic communication network constitutes more than 95% of the total capital expenditure of this system, it is clear that this type of network represents the most critical infrastructure without which the response time of the system may be much higher than 10 milliseconds. On the other hand, the operational cost of this system would be around a sixth of the cheapest complete alternative solution – adding diesel generator redundancy. The case study under investigation at present only applies to off-grid industrial applications but the wider societal benefits of the project are promising particularly in places with an unstable electricity grid. The solution also results in reduced secondary carbon emissions due to the requirement of less diesel generators. This offset can be accounted for in the transportation of parts required in the manufacturing process of diesel generators, as well as emissions created during the manufacturing process itself.

10. Recommendations and Future Work

The demand management system functions as expected, but there are several limitations that are recognized and outlined in this section.

- The present simulation scheme cannot account for multiple faults in the grid during one simulation. It is likely that several modifications in the generation section and control scheme will be needed to overcome this constraint.
- The identified load groups for disconnection are discrete, so the total magnitude of disconnected loads can often exceed the power generation capacity lost. This can potentially be resolved by incorporating variable speed drive technology to transform the loads into continuous variables.
- The absence of a contingency plan to cope with possible failure of the power management system.

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Appendix

Appendix A: Work breakdown structure and RACI Matrix

Work Breakdown Structure
Name of Project: Load management for off-grid industrial applications

Project Start	Wed, Mar 2, 2022

Critical path: Indicates tasks that determine the timely completion of the project

Level	WBS	Task Description	Assigned To	Start	End	Notes
1	1	**Initiation**				
2	1.1	Defining the system	Everyone	05/03/2022	28/03/2022	
2	1.2	Background research	Everyone	14/03/2022	12/06/2022	
3	1.3.1	Designing the system	Everyone	28/03/2022	12/06/2022	
3	1.3.2	Creating a diagram/block diagram of control system	Nuril & Emmanuel	28/03/2022	17/06/2022	
3	1.3.3	Hardware selection and design on communication network	José, Sahan, Jana, Emmanuel	12/06/2022	01/10/2022	
2	1.4	Consultation with supervisors about the elements and the whole system	Everyone	28/03/2022	20/06/2022	
1	2	**Data analysis**				
2	2.1	Data collection and processing: create models from the data	Sahan & Jana	17/05/2022	24/05/2022	
1	3	**Modelling and simulation**				
2	3.1	Simulink modelling and simulation	Emmanuel, Jana, Nuril	02/05/2022	12/06/2022	Summer Target: 12 June 2022
2	3.2	Machine learning	Emmanuel, José, Sahan	01/09/2022	02/10/2022	Summer Target - decision to implement is TBD
2	3.3	Building LabVIEW system	Emmanuel & Jana	01/09/2022	07/10/2022	
2	3.4	User Interface design	Emmanuel & Nuril	07/10/2022	28/11/2022	
1	4	**Socio-economic analysis**				
2	4.1	Cost analysis	Jana, Sahan, Nuril	02/05/2022	16/12/2022	Working duration target for summer presentation
2	4.2	Cost savings compared to diesel generator-only system with redundancy	Sahan, Nuril, Jana	02/05/2022	16/12/2022	
2	4.3	Social impact of the system in application	Nuril, Jana, Emmanuel	02/05/2022	14/11/2022	
2	4.4	Sustainability of the project	Sahan, Jana, Nuril	28/10/2022	14/11/2022	
1	5	**Project deliverables**				
2	1.1	Barcelona Interim Report	Everyone	02/05/2022	22/06/2022	
2	1.2	Barcelona Interim Presentation	Everyone	02/05/2022	27/06/2022	
2	1.3	Final Report	Everyone	01/12/2022	12/16/22	
2	1.4	Final Presentation	Everyone	01/12/2022	16/12/2022	

Figure 31: Work breakdown structure

Tasks	Status	Sahan Tampoe	Emmanuel Mompremier	Jana Dundure	Nuril Hidayati	José Martinez	Thierry Boileau	Ye-Qiong Song	Justin Chiu	Industrial partner
		Project team					*Supervisors*			
Initiation										
System definition		A	R	R	R	R	C	C	C	C
System design		R	R	R	R	A	C	C	C	C
Block diagram of control system		I	A	I	R	I	C	I	I	I
Hardware and communication		A	R	R	I	R	I	C	I	I
Data analysis										
Data collection and processing		A	I	R	I	I	C	C	I	C
Modeling										
Simulink		R	A	I	I	R	C	C	I	C
Machine learning		R	R	I	I	A	C	I	I	I
LabVIEW		I	A	R	I	I	C	I	C	I
User interface		I	A	I	R	I	C	C	C	C
Socio-economic analysis										
Cost analysis		R	I	R	A	I	I	I	C	C
Cost savings analysis		R	I	A	R	I	I	I	C	C
Social impact		I	R	A	R	I	I	I	C	C
Environmental impact analysis		R	I	R	A	I	I	I	C	C
Report writing and presentations										
Barcelona interim report		R	R	R	R	A	C	C	C	I
Barcelona interim presentation		R	R	A	R	R	C	C	C	I
Final report		A	R	R	R	R	C	C	C	I

R	Responsible
A	Accountable
C	Consulted
I	Informed

Figure 32: RACI Matrix

Appendix B: Memo of meeting

Memo of Meeting – Challenge Based Module

I. Meeting 03

Date: Monday, 4 April 2022

Attendees:

- DENSYS students: Emmanuel, Sahan, Jana, Nuril, José
- Academic Supervisor: Prof. Ye-Qiong Song, Prof. Thierry Boileau, and Prof. Justin

Meeting objectives:

- Discussing the starting point of the technical part; communication network, hardware selection, and control system

On Communication Network

- Options of communication network used:
    - Multimode fiber optic and 4G routers
    - Wireless solution: directional wifi solution which can cover more than 1 km coverage → can provide high bandwidth, low price, and we can cover long distance
    - LORA technology to be looked at
- We might need to also take into account the cost optimization from choices above.
- Private 5G → but this is still in a research stage. We still can not find the product.
- **Follow up from Prof. Song:**
    - Where the sensor is located
    - What information we want to transmit from the sensor
    - In which form, frequency, and latency limit of the sensor.

On Hardware Selection → will be easier to discuss after knowing the detailed operation of the existing plant

On Control System

- Are we proposing a system from scratch? To propose the cheapest solution: we need to maximally use the existing system
- **Additional details on Thierry's explanation:**
    - Define to what level we want to go - the scope of our work-. To the Level of the electrical system or only to produce binary outputs like 0 and 1. If we want to do the latter we don't need information about the electrical part, but it wouldn't be that much of a challenge. It would basically be a program with automatic selection with which loads we can use or not. In addition, we need to know important information such as the number of loads, the power of each load, and the ranking of the loads in order of priority.
    - The simulation could be done with two generators, one with a given value, and the second with variable power. Then we add loads. We create an algorithm that creates or disconnects the loads in order to always have consumed power *greater or equal* (it was probably meant to mean lower or equal) to the power given by the generators. This can

Figure 33: Memo of meeting

Appendix C: Data analysis

- **Data Understanding**

The data received from the industrial partner comprises 3 datasheets in the form of Excel files. These datasheets represent the variation of the parameters of the microgrid on a given day (in this case: 1 August 2021, 13 August 2021 & 21 December 2021) in which a system failure occurred.

The file labeled *1 August 2021* contains 1000 data entries (rows) and 70 parameters (columns) storing data every minute.

The file labeled *13 August 2021* contains 5389 data entries (rows) and 66 parameters (columns) storing multiple data points per minute.

The file labeled *21 December 2021* contains 1000 data entries (rows) and 69 parameters (columns) storing data every minute.

- **Data Preparation**

Since the datasheets did not include any duplicate values (rows or columns) nor missing values that could hinder the purpose of the present analysis, the data preparation step consists mainly in identifying the parameters in the files that would be relevant for the task. With expert knowledge and a first exploratory analysis, the amount of relevant parameters have been reduced to 10 namely

1. *Date*
2. *Time*
3. *ID of the Controller attached to a Given Generator*
4. *Active Power*
5. *Grid Frequency*
6. *Generator Frequency*
7. *Content of the Alarm Notification*
8. *Current Phase 1*
9. *Current Phase 2*
10. *Current Phase 3*

	Date	Time	Controller	Pwr	Gfrq	Bfrq	Reason	Ig1	Ig2	Ig3
0	2021-08-01	17:16:00.4	C05 - SGP 1309	34.0	50.0	50.0	Time stamp	68.0	71.0	72.0
1	2021-08-01	17:16:00.2	C03 - SGC 1618	48.0	50.0	50.0	Time stamp	91.0	80.0	84.0
2	2021-08-01	17:16:00.1	C02 - SGC 1617	50.0	50.0	50.0	Time stamp	101.0	91.0	96.0
3	2021-08-01	17:16:00.1	C01 - SGB 1603	39.0	50.0	50.0	Time stamp	77.0	68.0	88.0
4	2021-08-01	17:16:00.1	C04 - SGC 1615	40.0	50.0	50.0	Time stamp	84.0	81.0	91.0

Figure 34: Snippet of the curated data

- **Dashboard**

The results of the implementation of *DMSystem Controller* and various insights drawn from the data analysis have been aggregated into a dashboard. Screenshots are shown below, and a video overview is available on [YouTube]().

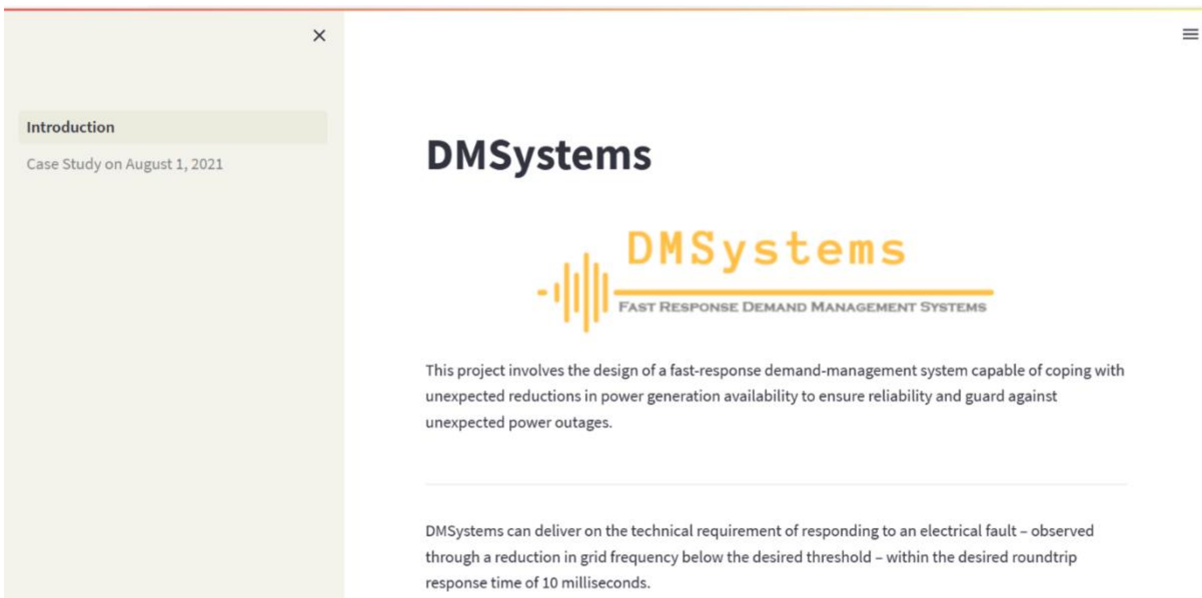

Figure 35: Overview of the purpose of DMSystems

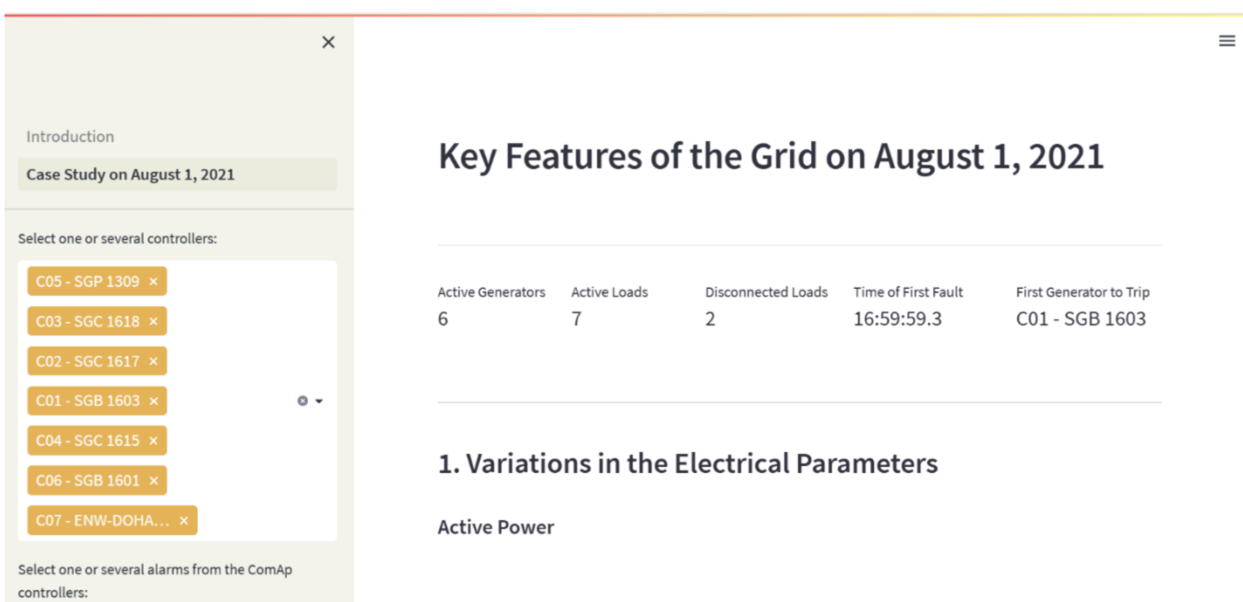

Figure 36: Main electrical features of the grid on the day August 1, 2021

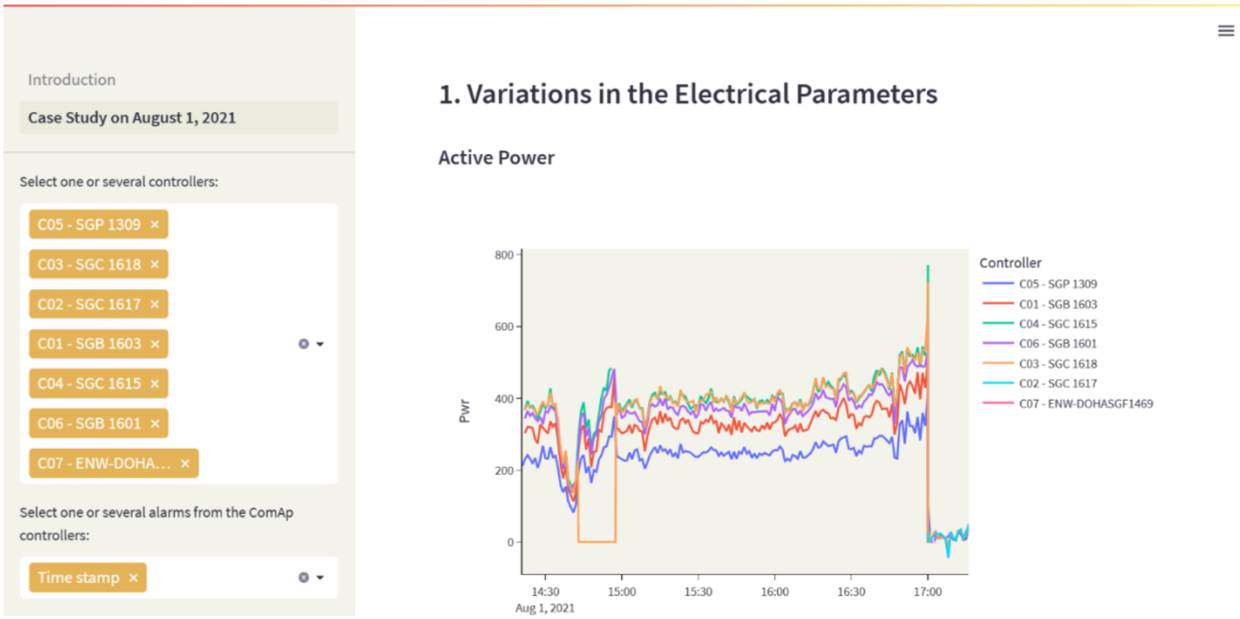

Figure 37: Dynamic variation of each controller over time

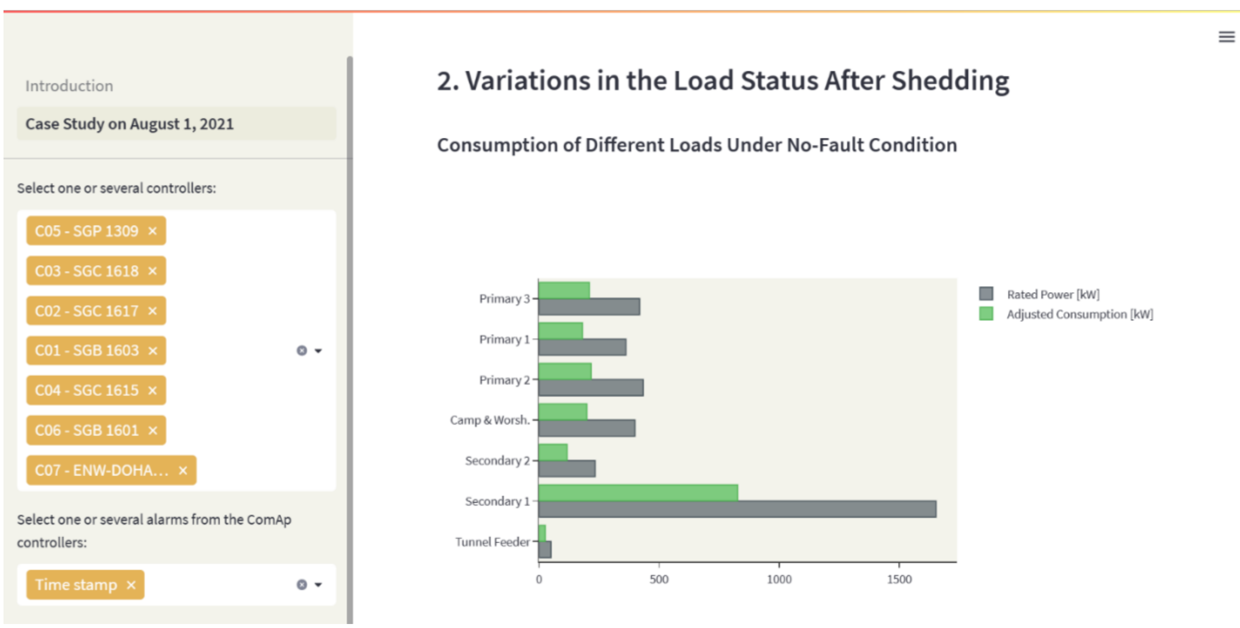

Figure 38: Actual power consumption of the load groups compared to their rated power

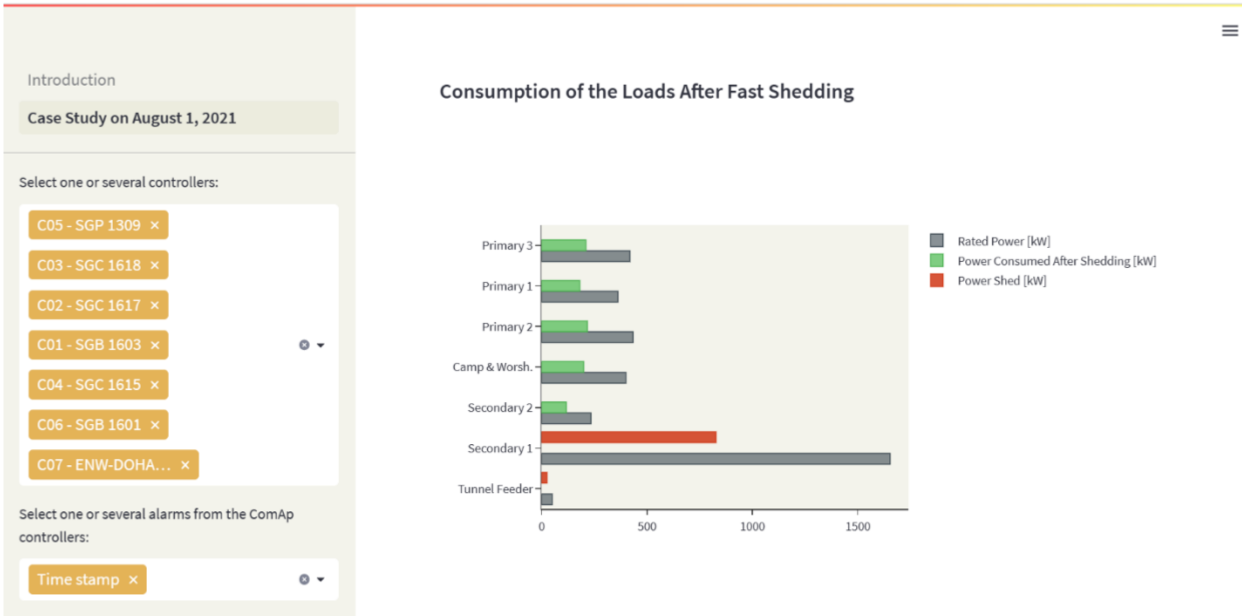

Figure 39: Identification of the load groups disconnected following generator trips

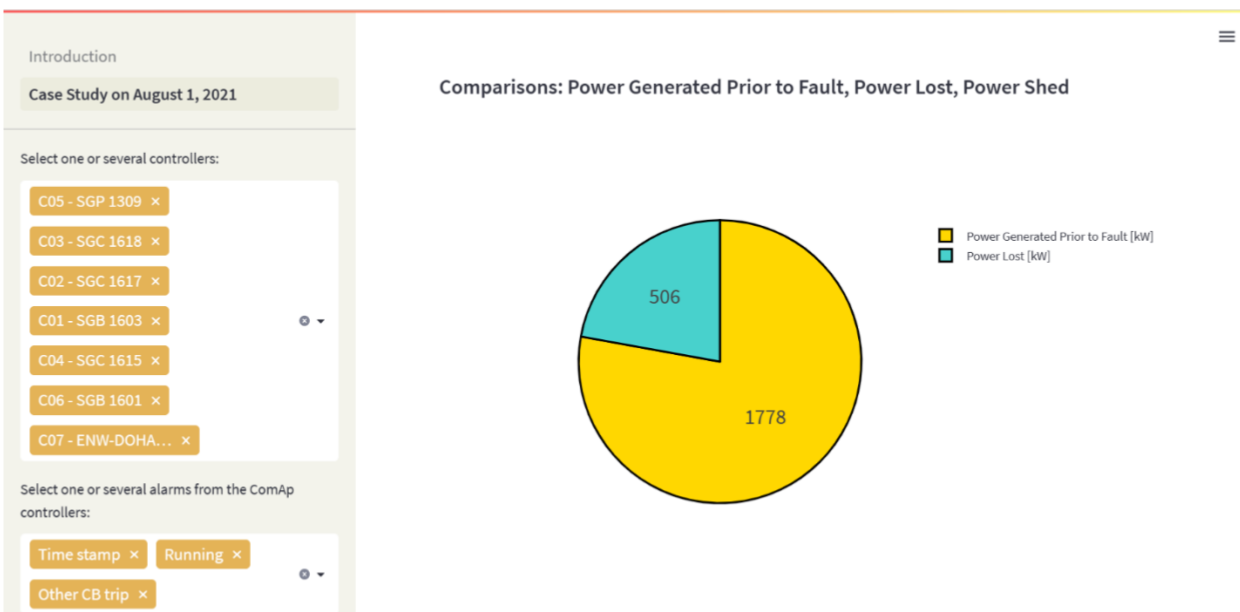

Figure 40: Proportion of power lost in the grid due to generator failures

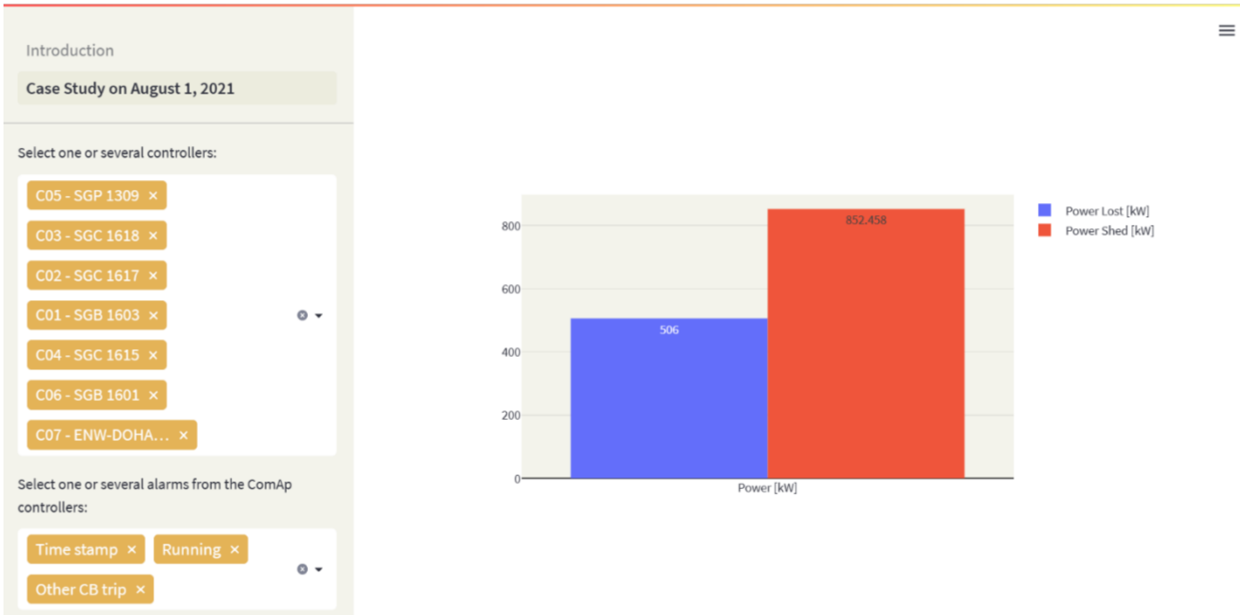

Figure 41: Comparison between the power lost and power shed as a mitigation solution

Appendix D: Single line diagram (SLD) of plant

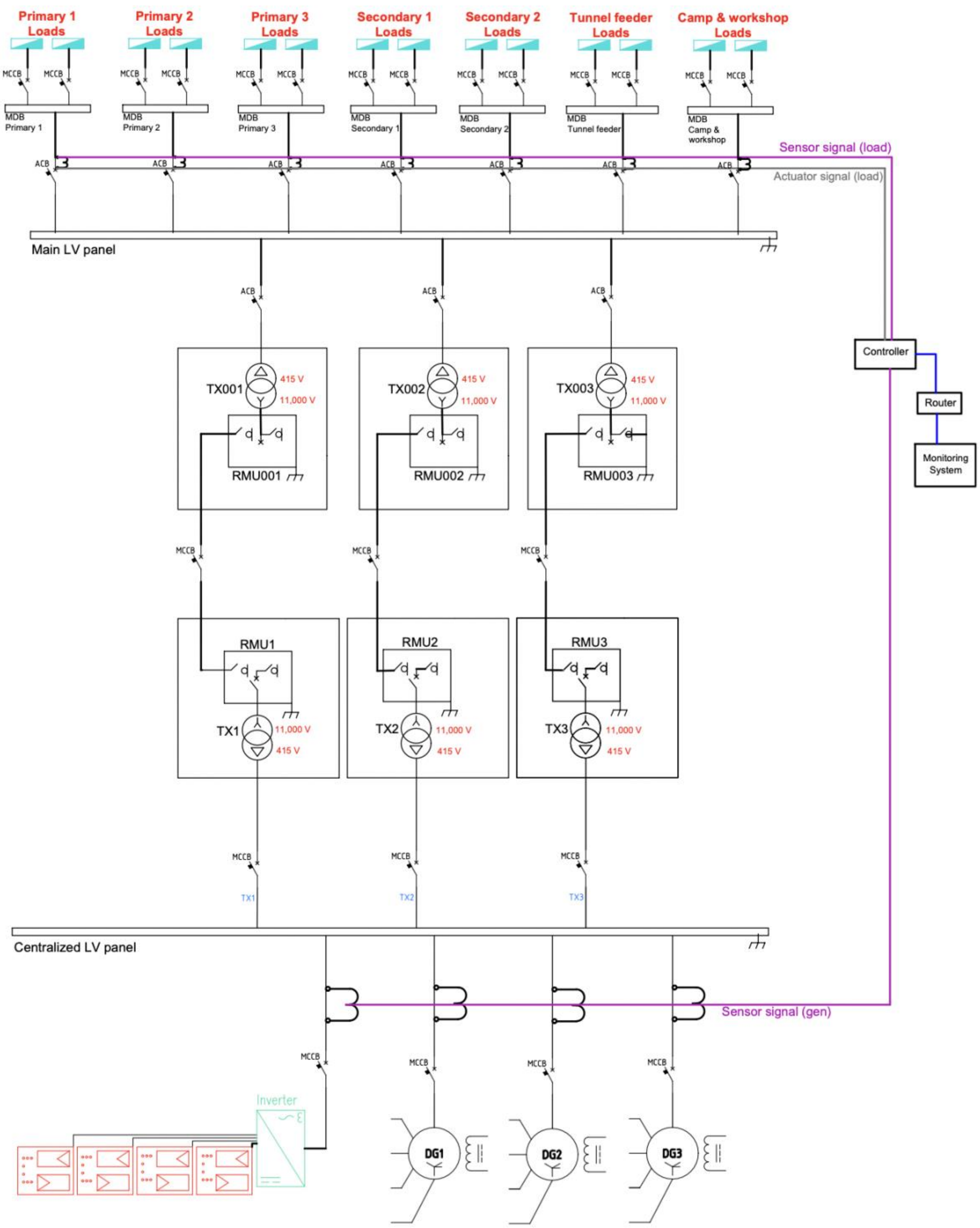

Figure 42: Single line diagram depicting electrical setup of plant

Appendix E: Communication network response time using different PCs

1. Data rate of Ethernet: 130 Mbps. CPU @ 2.20GHz. RAM 16.0 GB

```
PS C:\WINDOWS\system32> Get-NetAdapter | select interfaceDescription, name, status, linkSpeed

interfaceDescription                                name                          Status LinkSpeed
--------------------                                ----                          ------ ---------
VMware Virtual Ethernet Adapter for VMnet8          VMware Network Adapter VMnet8 Up     100 Mbps
VMware Virtual Ethernet Adapter for VMnet1          VMware Network Adapter VMnet1 Up     100 Mbps
Killer Wireless-n/a/ac 1535 Wireless Network Adapter Wi-Fi                         Up     130 Mbps
```

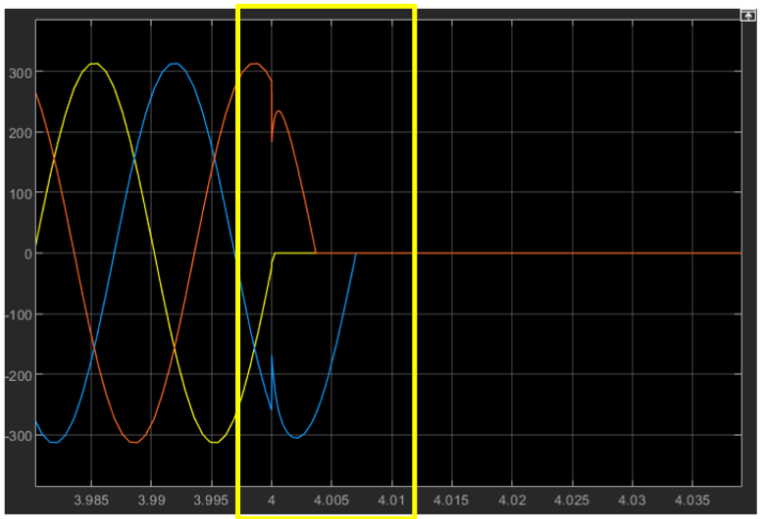

Figure 43: Ethernet data rate and Simulation response time for PC #1

2. Data rate of Ethernet: 72.2 Mbps. CPU @ 2.80GHz. RAM 16.0 GB

```
PS C:\WINDOWS\system32> Get-NetAdapter

Name                      InterfaceDescription                    ifIndex Status       MacAddress             LinkSpeed
----                      --------------------                    ------- ------       ----------             ---------
Wi-Fi                     Intel(R) Wi-Fi 6 AX201 160MHz                16 Up           14-18-C3-6C-30-D1      72.2 Mbps
Connexion réseau Bluet... Bluetooth Device (Personal Area Netw...       8 Disconnected 14-18-C3-6C-30-D5         3 Mbps
```

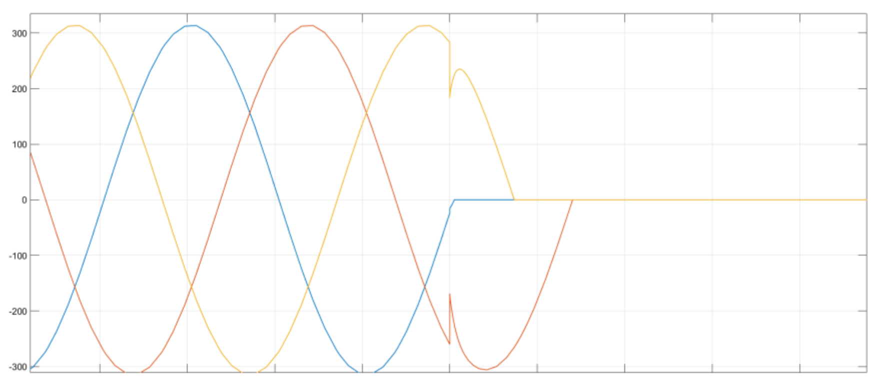

Figure 44: Ethernet data rate and Simulation response time for PC #2

Find Ethernet data rate

Open Windows Powershell from search bar. Right click, choose ‘Run as Administrator’ and type in the following command + press Enter.

```
Get-NetAdapter | select interfaceDescription, name, status, linkSpeed
```

To find PC specs

Click on the Windows Start button, then click on Settings (the gear icon). In the Settings menu, click on System. Scroll down and click on About. Include processor, Memory (RAM), etc