

DENSYS

MASTER ERASMUS MUNDUS | DECENTRALISED SMART ENERGY SYSTEMS



CHALLENGE-BASED MODULE

DEMAND MANAGEMENT FOR POWER-CRITICAL OFF-GRID INDUSTRIAL APPLICATIONS

FINAL REPORT

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Executive summary¹

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 preliminary results from the simulations demonstrate that the system can respond to reduced power generation availability identified in the form of declining system frequency or voltage below a defined threshold within a desired roundtrip response time of 10 milliseconds. In addition, the initial financial assessment indicates that the operational expenditure of the demand-management system would be around 80% cheaper than adding redundancy. Environmental benefits in the form of reduction in secondary emissions will be investigated quantitatively as the project progresses.

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.

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 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.

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.

System Design

Adopted from the NASA Systems Engineering Handbook², 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.

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.

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.

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 plant³

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 load⁴.

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.

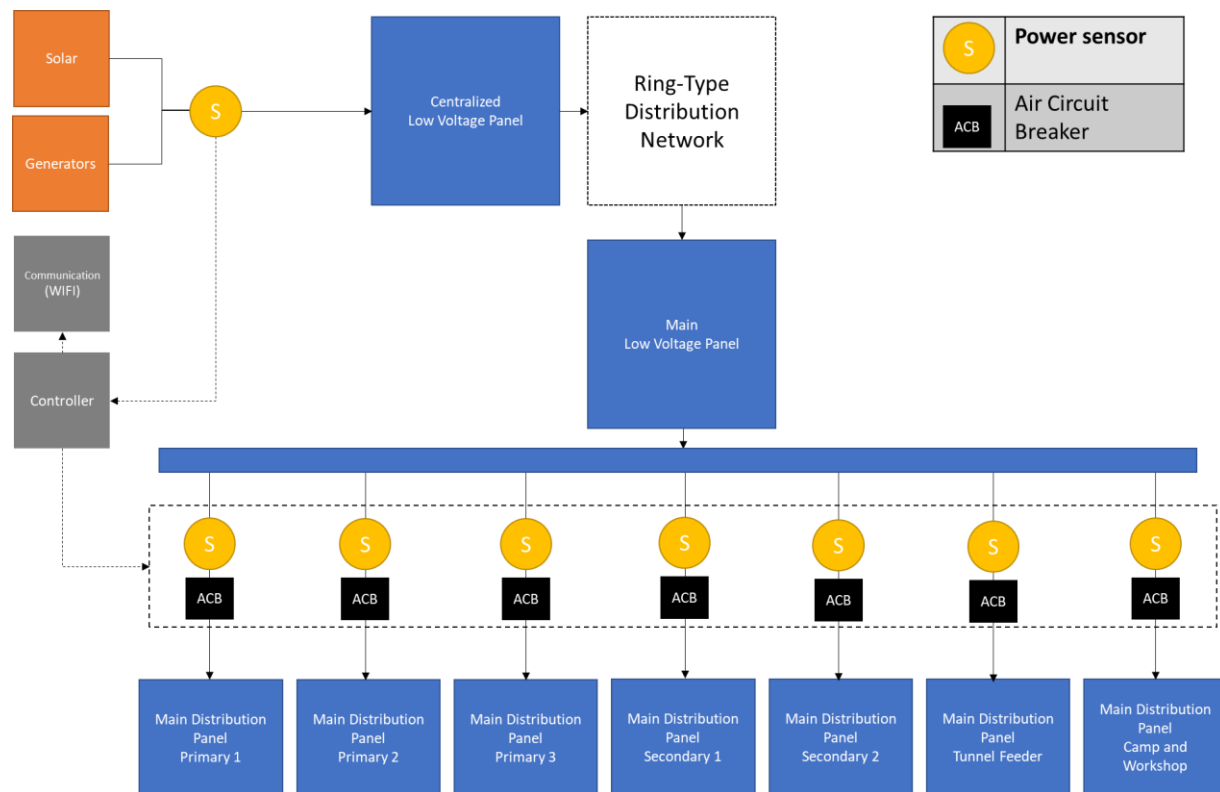


Figure 1: Block diagram of the industrial plant

³ Based on information provided by the industrial supervisor

⁴ <https://www.lucyelectric.com/what-is-a-ring-main-unit>

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

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.

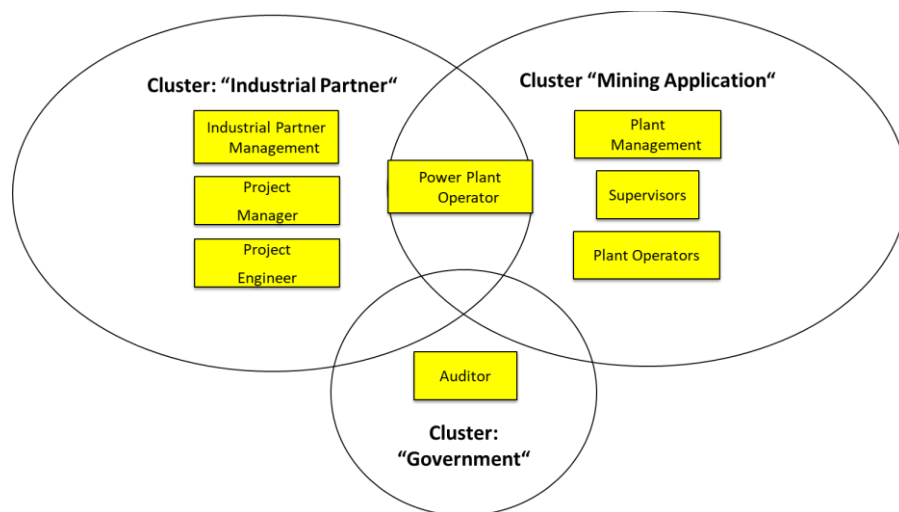


Figure 2: Defining and clustering stakeholders and target groups

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 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	Design around user friendliness.

	the plant that are affected directly by the controller.	
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		

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 notifications and active power, current, voltage, frequency variations registered by the ComAp controllers overseeing the entire power generation side of the grid. Here are samples 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

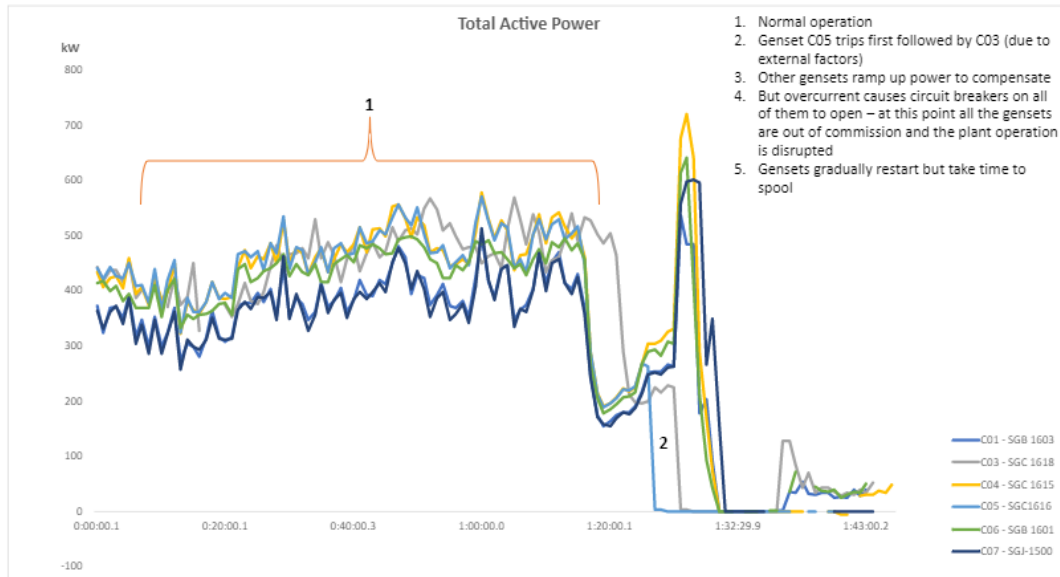


Figure 4: Active power variations of the generators

The genset C03 trips at 1:24:48.0 pm followed by C05 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 minutes (around 10 minutes) after the failure.

In the following section, the mitigation of the consequences of overload are proven via fast load shedding.

Fast Load Shedding

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, one of the production units trip, 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 speed of frequency change depends on power mismatch and inertia of the system (4).

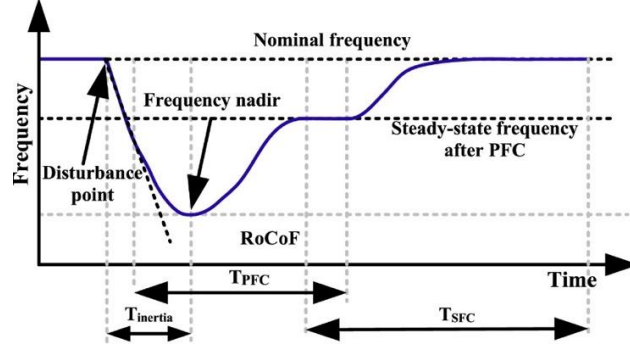


Figure 5: Frequency response and regulation of synchronous machines

Frequency response and regulation of synchronous machines (4).

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. Adaptive 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 inertia constant accurately. Inaccurate initial slope or inertia may lead to poorly estimated imbalance (5).

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. 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 (5).

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 (6).. The load mismatch between generated power and load power can be calculated using the *Swing Equation* (7). The inertia constant is the kinetic energy over the system base power.

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

Analysis of a power disturbance and modelling of system frequency response

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



Figure 6: Grid failure on August 1, 2021

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

Table 4: Faults identified by DMSsystem Controller in the grid logs

	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

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

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 that can help prevent blackouts.

Methodology & control strategy of the power management system

Our fast response demand management system labelled "*DMSystem Controller*" is an intelligent controller which monitors the grid's condition and performs actions to maintain the system stability. *DMSystem Controller* can read the multifunctional relays and has access to the necessary information to open the load breakers. In general, a power management system consists of a complete integration of protection relays (voltage & frequency), remote I/O modules, communication network, and monitoring devices (8). To prevent increase/decrease in frequency/voltage of the grid, control approaches such as underfrequency load shedding, undervoltage load shedding and their counterparts overfrequency/voltage load shedding have been considered.

When a disturbance (generator trip, etc.) occurs in the grid, *DMSystem Controller* should shed load groups according to the priority list detailed in Table 1 within 10 milliseconds. It is worth noting that load shedding action will be considered 100 milliseconds after the fault occurrence; these 100 milliseconds include input and output processing time in the remote I/O modules, program execution time of the PLCs and breaker opening time delay (8).

The step-by-step control procedure 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). The ComAp Reference Guide refers to *BOC ShortCurr* as an overcurrent protection; *BOC IDMT* as current/voltage unbalance, active power, shortcurrent and earthfault 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 Table 6 to propose the amount of loads to disconnect. Figure 7 details the power availability assessment made by *DMSystem Controller* and the recommendation to disconnect a total of 506 kW load power.

Table 6: *DMSystem Controller Load Shedding Strategy*

Load Shedding Strategy
<ol style="list-style-type: none"> 1.- Identify the fault occurrences 2.- Sum the power generated 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 for the loads 6.- Determine by how much the total load power should be reduced 6.- Determine which loads should be disconnected 7.- Send the appropriate load shedding commands

```

-----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 7: Assessment of the power imbalance made by the controller

Based on the load disconnection priority defined by the industrial partner and reported in Table 1 and Figure 8, a load shedding scheme has been established to cope with the power generation shortage.

-----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 & Workshop     400
Primary 2           434
Primary 1           362
Primary 3           419

```

Figure 8: Active loads in the grid

Accordingly, the *DMSysSystem Controller* has proposed to disconnect the first 2 load groups (Tunnel Feeder & Secondary 1) whose cumulated rated power amount to 1703 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, 1703 kW will be effectively disconnected.

```

-----DISCONNECTION-----
The quantity of load group to be disconnected is 2 i.e [50, 1653]
The disconnected power is 1703 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 9: Assessment of the load groups to be disconnected

The resulting set of commands to be transmitted to the circuit breakers appears in Figure 10. 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 10: Disconnection commands sent to the circuit breakers

A suitable communication network (see next chapter on the 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) if no action is taken Table 4. Once the controller accurately detects and deals with fault 1, the additional faults shown in the table will be avoided.

A simplified replica of the grid has been designed and simulated in MATLAB/Simulink to showcase the effectiveness of the proposed control scheme.

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.

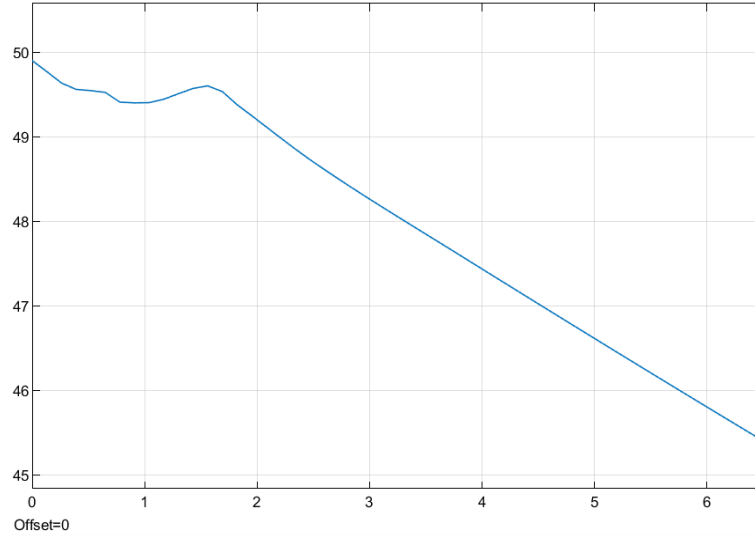


Figure. System Frequency response during power disturbance

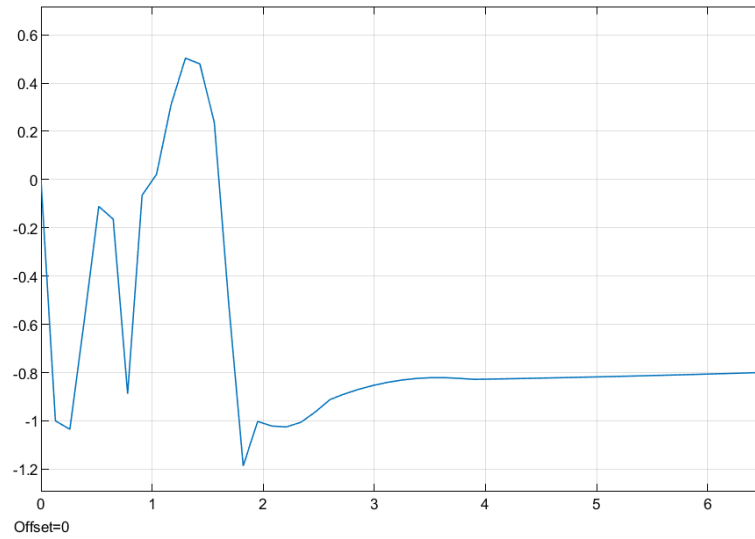


Figure. Calculated rate of change of frequency df/dt (ROCOF) from system frequency response

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 equal and rated for 800 kVA, then the total base power is 4000 kVA and the total Inertia becomes:

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

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

Using the inertia estimation, and other available data, a Simulink model of the system frequency response has been elaborated. The next plot shows system frequency response when trying to replicate the power disturbance from the experimental data.

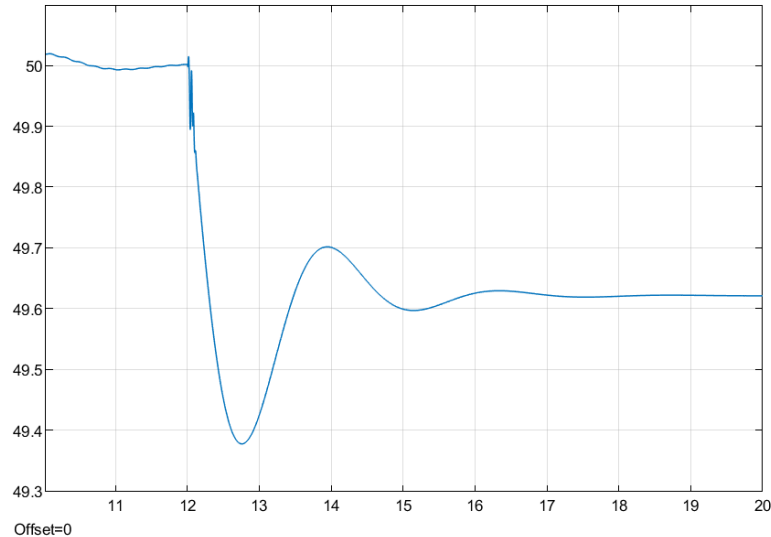


Figure. System Frequency response during power disturbance simulated in Simulink

Communication Network

The proposed design of the communication network is presented in Figure 12. 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.

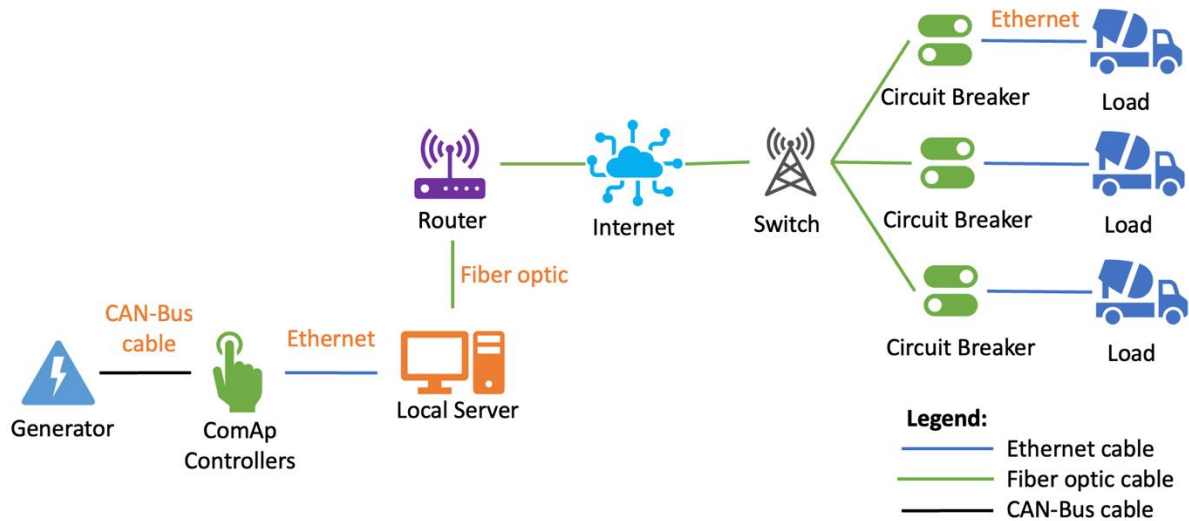


Figure 11: Server-client model and data communication on TCP/IP platform

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 *DMS*System 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 13. 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 (9). 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 6. Additionally, this local server will also run the SCADA as the system is remotely controlled.

The load shedding commands originating from the *DMS*System 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 12: Recommended communication cables for ComAp controllers based on its communication guide

Table 7: Comparison between Modbus RTU and Modbus TCP/IP (10) (11)

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 consume the disconnection commands being transmitted. The said commands will dictate whether a circuit breaker should open or remain close. As analyzed in the electrical grid section, 7 load groups with distinct rated power and circuit breaker connect to the plant contrasting with the 3-load network depicted in Figure 12. Besides the main components mentioned before, the communication network might be completed with other accessories such as connectors, couplers, splices, multiplexing devices, and amplifiers.

Throughout the fiber optic lane spanning from the local server to the circuit breakers, TCP/IP protocol is involved. This protocol has been used to transmit the data from the simulation to the real world and receive it back without data loss. 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 protocol 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 14. (12)

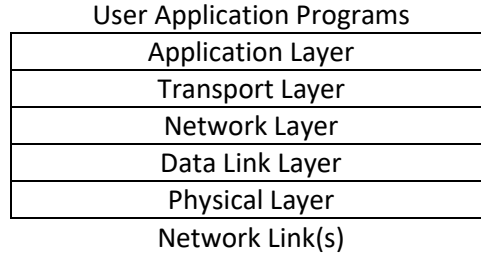


Figure 13: The five layers of TCP/IP (12)

Furthermore, TCP/IP protocol has been used in previous works serving similar purposes as this demand management system. In (12), the TCP/IP is integrated with smart meters within a distribution network, and (13) employed the protocol in the microgrids typology of an intelligent load management system. The later work 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 understudy 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.

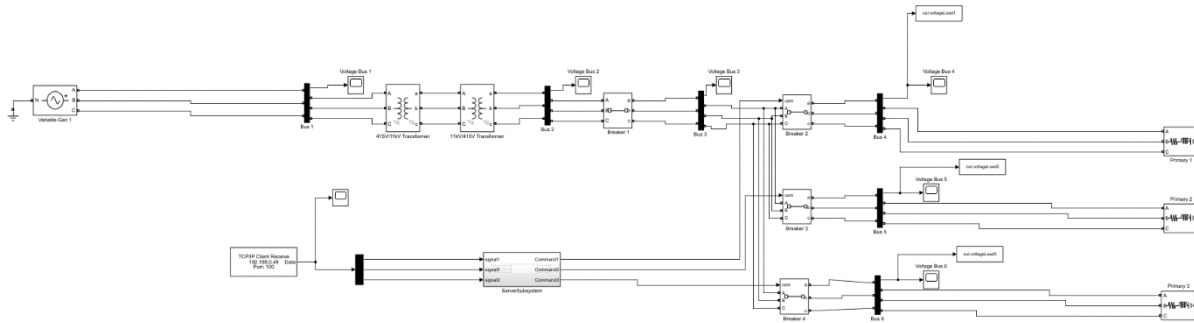


Figure 14: Scheme of the Communication Network

The communication network modelled in Figure 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.

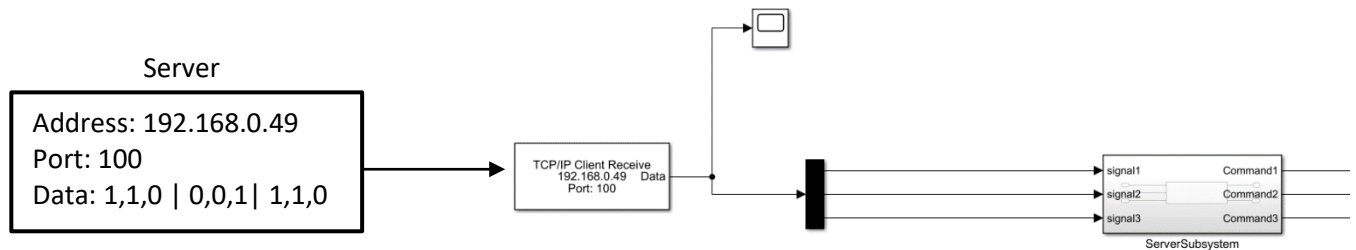


Figure 15: Server-Client data transmission

The 10-second simulation proposes to transmit 3 sets of commands from the server to the client and then to 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 $t = 8$ s. It is of importance to highlight that at $t = 0$ s, 4s and 8s, the Simulink simulation will wait for full and successful transmission of the sever data before proceeding. This characteristic allows to observe 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.

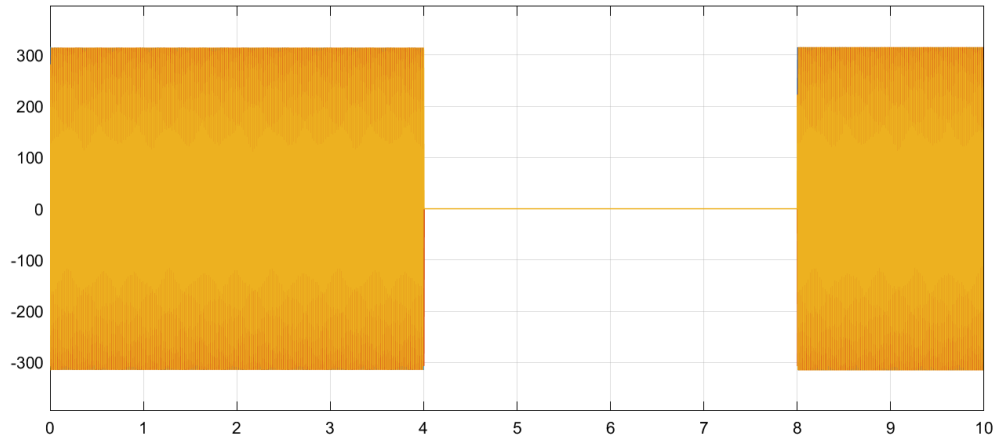


Figure 16: Voltage response of load group 1. Commands received $[t=0s: 1, t=4s:0, t=8s:1]$

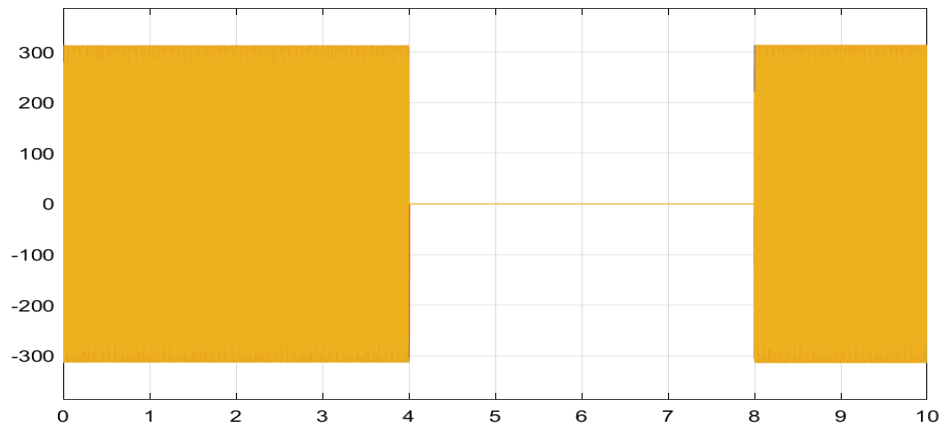


Figure 17: Voltage response of load group 2. Commands received $[t=0s: 1, t=4s:0, t=8s:1]$

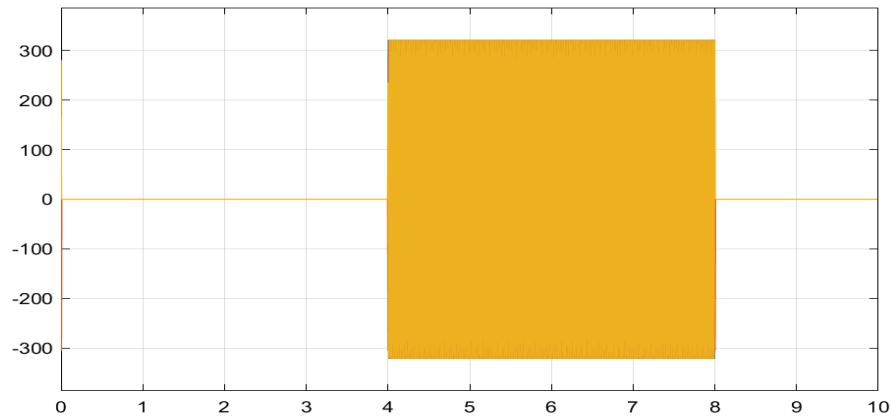


Figure 18: Voltage response of load group 3. Commands received $[t=0s: 0, t=4s:1, t=8s:0]$

A zoom into the voltage response of load group 2 around $t=4s$ when the circuit breaker receives the command 0 to disconnect the load group from the grid reveals that the processing time of the command signal falls below 10 milliseconds Figure. 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 ms. Since the load shedding commands can reach the circuit breakers in the said timeframe, 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 is done without considering the physical constraint of the components which might add delays and thus slow down the 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 (14).

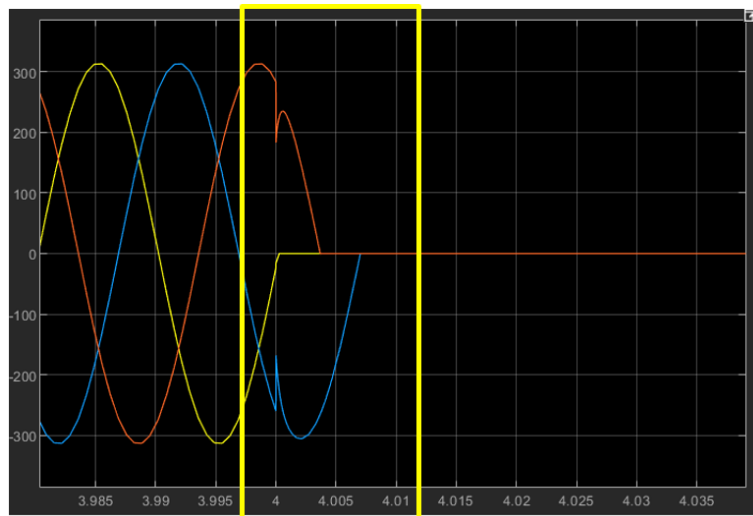


Figure 19: MATLAB and Simulink simulation result shows that the response time is achieved under 10 ms

Socio-economic and environmental analysis

Financial analysis

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

The financial analysis consists of preliminary calculations of total capital expenditure (CAPEX) and operational expenditure (OPEX) for the proposed system. The CAPEX includes control system and communication network, and 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.

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	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	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 investments into fiber optics communication network, that accounts for 97% of the total costs. Communication network is a critical infrastructure, as it allows to achieve the 10ms response time target and ensures reliability of the whole system. However, as the costs are a major reason why the system is needed in the first place, the solution is less likely to be adapted due to the high costs. Therefore, the authors advice to reconsider the whole communication network on the plant, investing in fiber optics communication for everything, not only the proposed load shedding system. That will allow to have much higher payback of communication network as a part of total business revenue, ensures reliable, fast, and safe communication, which is especially relevant for remote locations and extreme weather conditions.

The alternative is also present, as CAPEX with Ethernet communication network is also calculated and presented in the Table below.

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 the resulting CAPEX 90% of total costs still accounts for communication network, however the total cost is 4 times lower than for the solution with fiber optics communication network. However, the main trade-offs are reliability of the system and response time that might not be achieved with this communication network option. Ethernet communication is only suitable for 100m or below, meaning that every 100 meters there should be a switch. That increases the noise pollution produced by the system, as well as the quality of data received and the speed is also getting affected. As the main objective of the project is to develop a fast response solution, replacing the fiber optics communication network with ethernet connection is not advantageous enough compared to the posed risks of not achieving the main objective.

The financial analysis presented in this report covers the estimated total capital expenditure (CAPEX) and operational expenditure (OPEX) of the proposed solution, and the comparison of the OPEX with the alternative of adding diesel generator redundancy. The hardware selection for the system is yet to be finalized, so the cost of components mentioned in the expenditure analysis are based on average market values.

The CAPEX of the load shedding system includes all the hardware installed in the initial stage of the project. Details of the components, unit price, and the total price is presented in Table 8.

Table 8: CAPEX of the load shedding system

Component	Unit	Unit price (€)	No. of units	Total price (€)
Controller – Raspberry PI 4 B (8 GB)	piece	72.00	1	72.00
Fiber optic cable	m	2.85	1,500	4,275.00
Wi-Fi router	piece	550.00	1	550.00
Sensor – current transformer	piece	50.00	16	800.00
Voltage sensor	piece	40.00	16	640.00
Total				6,337.00

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 of the proposed solution is shown in Table 9.

Table 9: 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:

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

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 kVA⁵ engines. A combination of these are used to obtain the desired capacity of 4,800 kVA as shown in Table 10.

Table 10: 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

⁵ <https://www.cummins.com/en/in/generators/500-1010-kva-diesel-generators>

The capacity of redundancy is assumed to be 20% of the total capacity. This can be composed of a 650 kVA and a 300 kVA generator to obtain the desired 960 kVA. The corresponding OPEX of this redundancy is shown in Table 11.

Table 11: 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, as renting diesel generators only implies operational costs. The investment costs of the proposed solution are very high mainly due to the communication network, however operating the solution after the investment is cheaper than maintaining redundancy. Additionally, adding diesel generators to the system potentially increases CO2 emissions of the whole system and compromises the lifetime of the generators, that will eventually need repair and replacement. In that case, proposed solution with fiber optics communication network that is adapted to the whole system is more economically feasible in the long run and a better investment not only into more stable and reliable system, but also into more sustainable future.

Social and environmental impact

As the financial analysis shows, this solution can assist in the reduction of financial losses due to power shortages. The money saved can therefore be used in various ways, such as raising the salaries of employees or on research and development. Both examples can potentially help local communities and the planet, as research and development can be focused on the 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 (15). 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.

Interim conclusions

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 – be it voltage or frequency drop – within 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 with the lowest priority as soon as a power imbalance is detected in the grid. The long-term vision is to create a load management system applicable to all cases prone to sudden power generation failures so the subsequent parts of the project will focus on improving the robustness and reliability of *DMSystems*. Although approximate, the financial analysis performed at this stage suggest that the operational cost of the proposed 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.

Recommendations

The system modelling and simulation as currently implemented presents several limitations that need to be addressed in the second half of the project. The most important shortcomings include:

- Lack of a proper communication network to ensure that the trip commands sent by the power management controller can reach the circuit breakers in a roundtrip time of 10 milliseconds.
- 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 that constraint.
- Absence of a contingency plan to cope with possible failures of the power management system.

In addition, focus will be placed on the following key elements:

- Design of a suitable communication network, most likely using single-mode or multi-mode fiber-optic Ethernet.
- Precise selection of hardware components such as microcontrollers, voltage and current sensors, and internet routers based on predefined selection criteria.
- Detailed socio-economic analysis based on an in-depth literature review on how load shedding technologies are used in remote power-critical infrastructure.
- Comprehensive environmental impact study based on reduction in secondary emissions.

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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 20: Work breakdown structure

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

R	Responsible
A	Accountable
C	Consulted
I	Informed

Figure 21: 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 22: Memo of meeting

Appendix C: Case 1 – Under/Overvoltage Protection

With an impedance at the outlet of the generator

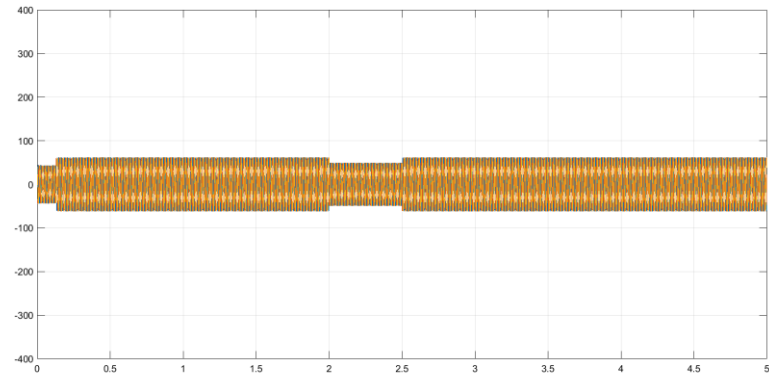


Figure 23: Voltage variation at the outlet of the programmable voltage source

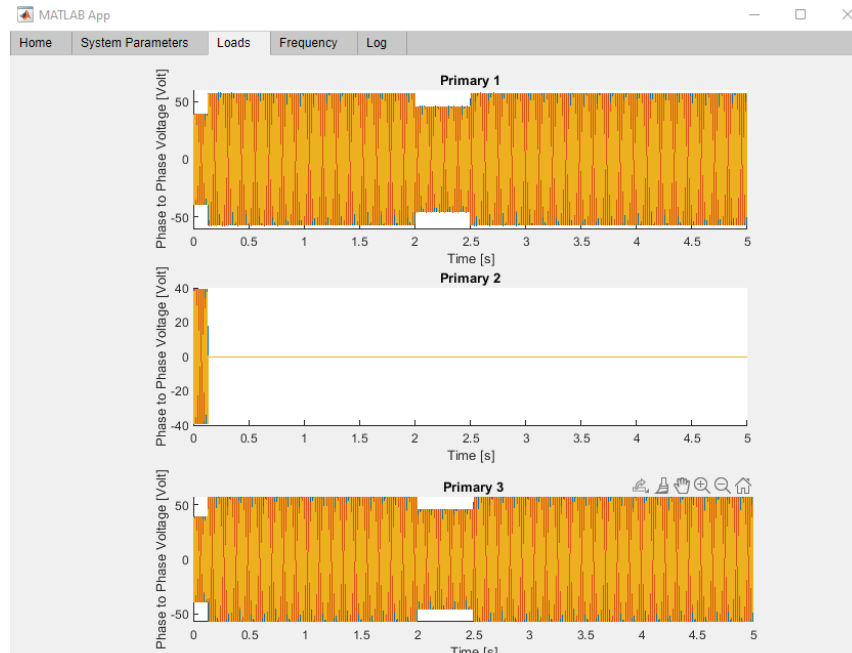


Figure 24: Behavior of Primary 1, Primary 2, Primary 3 under voltage protection with impedance

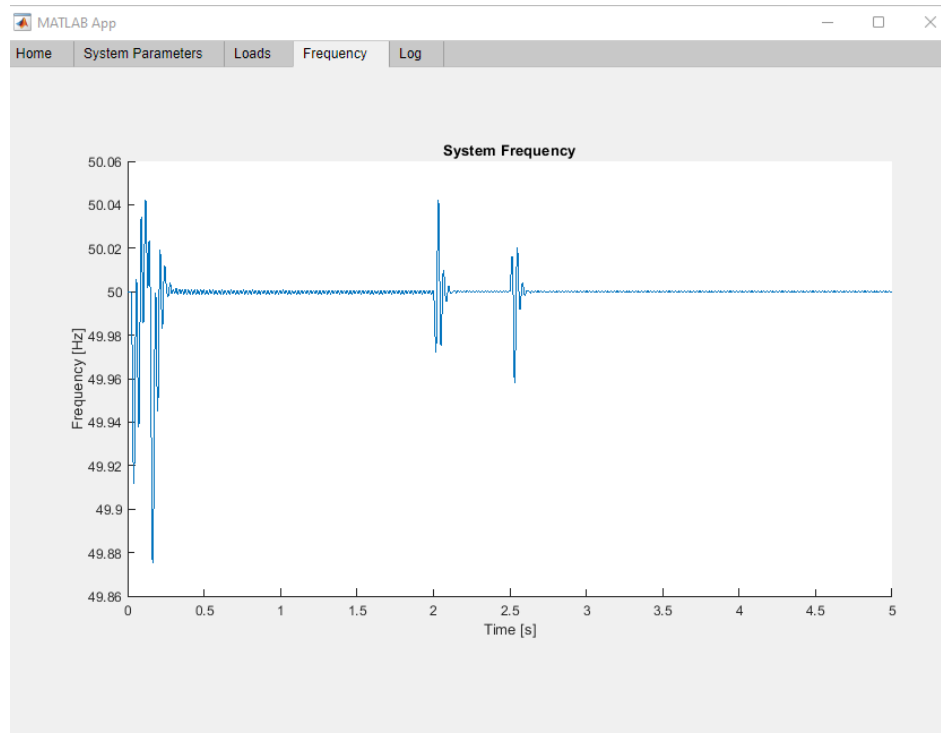


Figure 25: Behavior of system frequency under voltage protection with impedance

**Without
impedance**

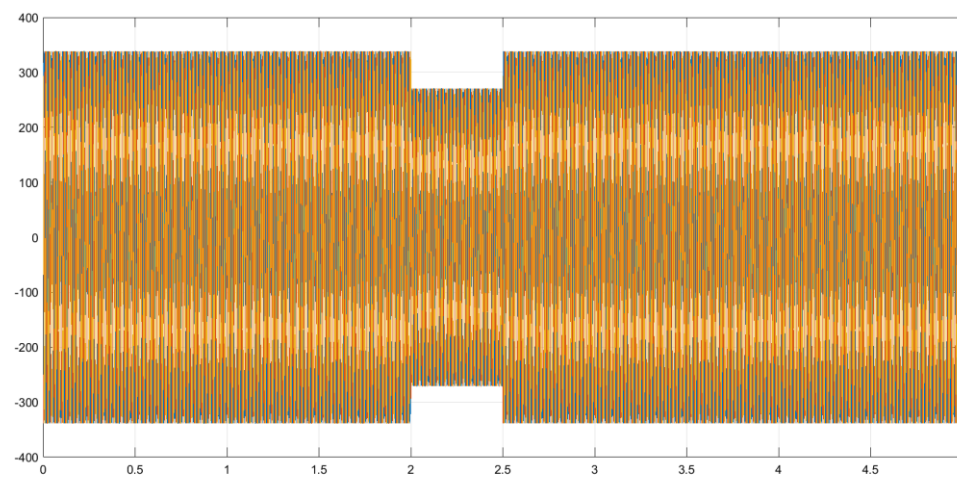


Figure 26: Voltage variation at the outlet of the programmable voltage source without impedance

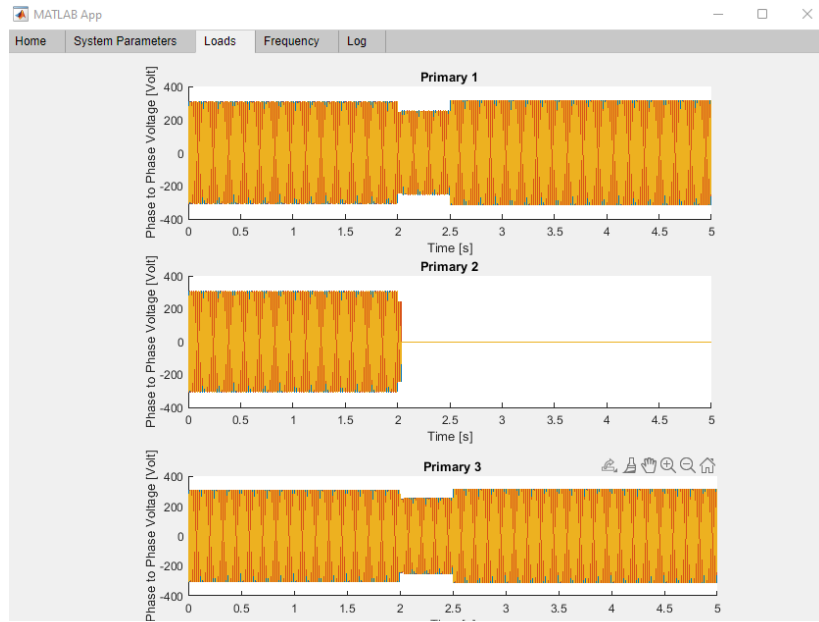


Figure 27: Behavior of Primary 1, Primary 2, Primary 3 under voltage protection without impedance

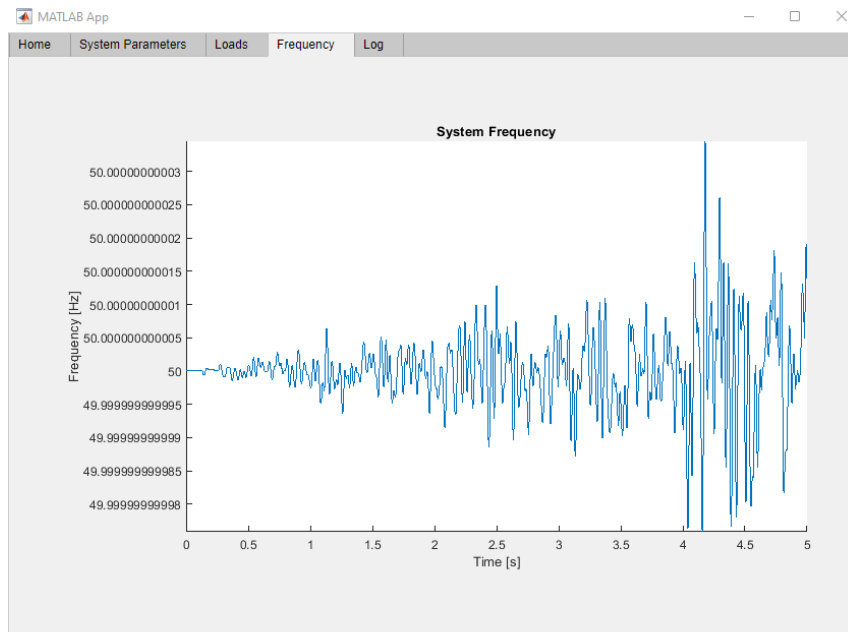


Figure 28: Behavior of system frequency under voltage protection without impedance

Appendix D: Case 2 – Under/Overfrequency Protection

With impedance at the outlet of the generator

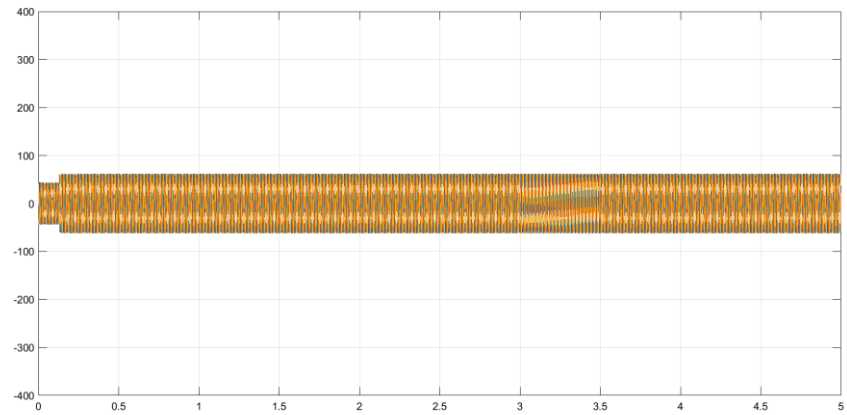


Figure 29: Voltage variation at the outlet of the programmable voltage source

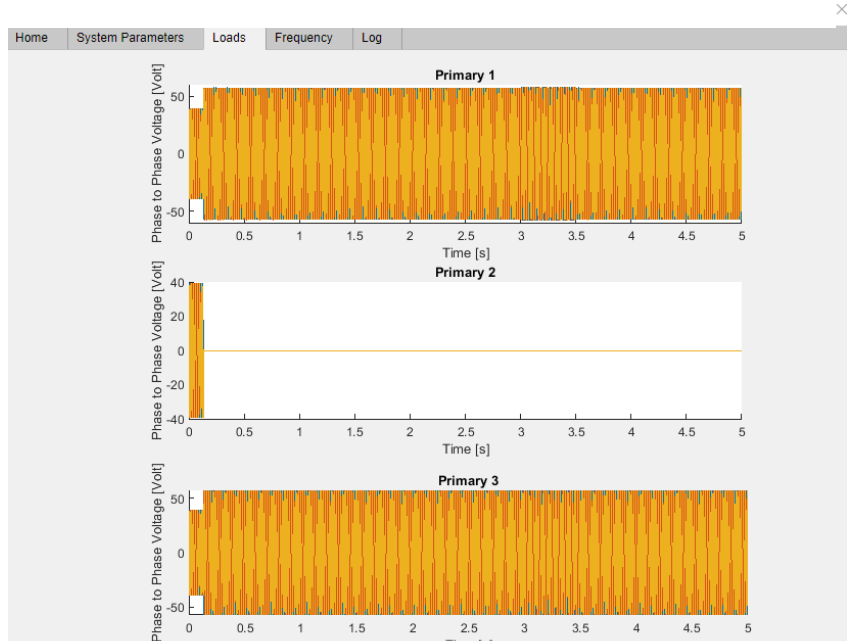


Figure 30: Behavior of Primary 1, Primary 2, Primary 3 under frequency protection with impedance

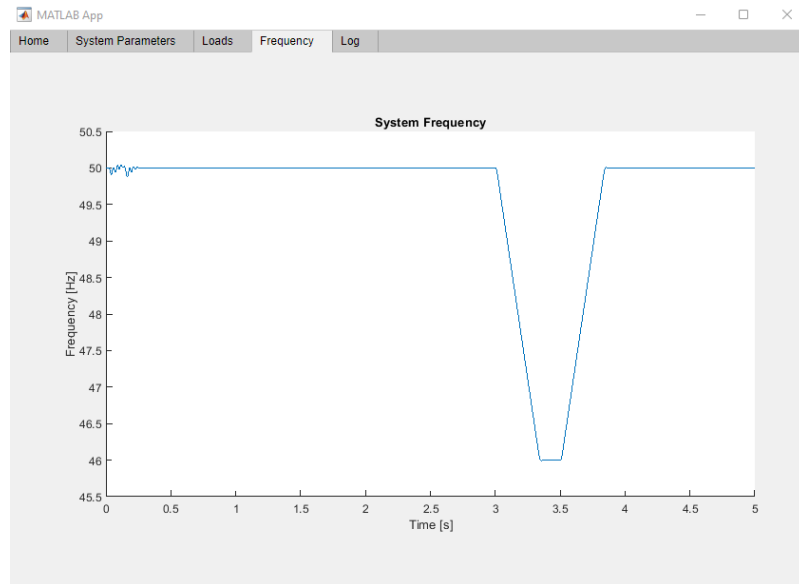


Figure 31: Behavior of system frequency under frequency protection with impedance

Without impedance

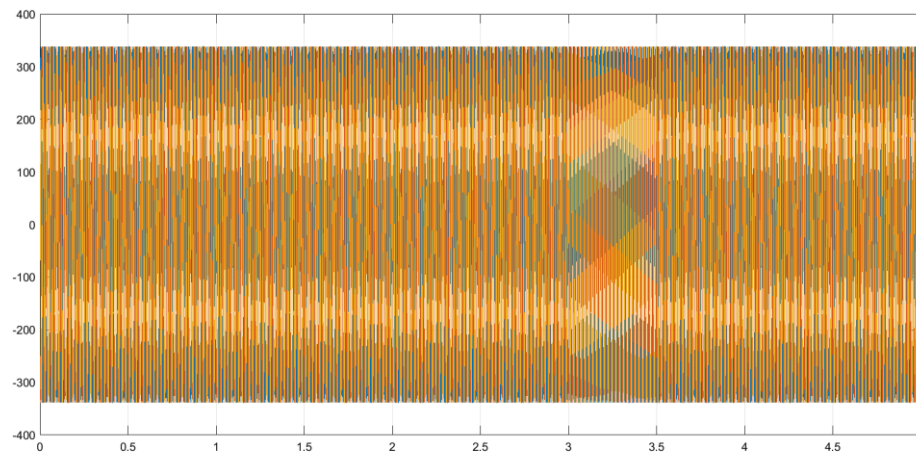


Figure 32: Voltage variation at the outlet of the programmable voltage source without impedance

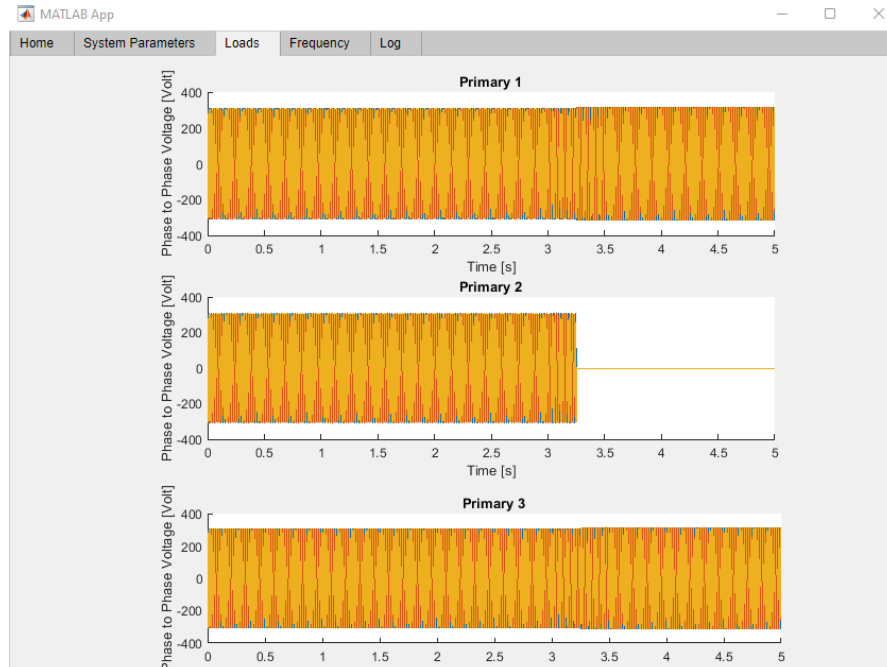


Figure 33: Behavior of Primary 1, Primary 2, Primary 3 under frequency protection without impedance

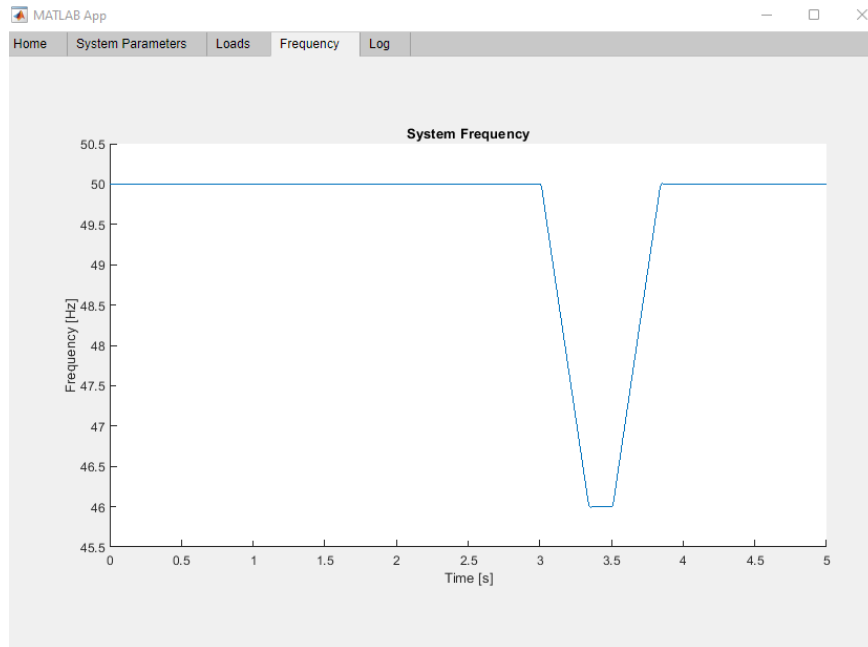


Figure 34: Behavior of system frequency under frequency protection without impedance