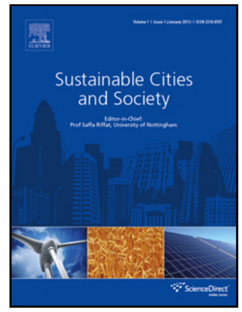
Accepted Manuscript



Title: Risk Analysis and Self-Healing Approach for Resilient Interconnect Micro Energy Grids

Authors: Yahya Koraz, Hossam A. Gabbar

PII: S2210-6707(17)30158-0
DOI: http://dx.doi.org/doi:10.1016/j.scs.2017.05.010
Reference: SCS 656

To appear in:

Received date: 18-2-2017
Accepted date: 14-5-2017

Risk Analysis and Self-Healing Approach for Resilient Interconnect Micro Energy Grids

***Yahya Koraz*[1] *and Hossam A. Gabbar*[1,2*]**

[1]Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa L1H7K4 ON, Canada

[2]Faculty of Energy Systems and Nuclear Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa L1H7K4 ON, Canada

Corresponding author: Hossam.Gabbar@uoit.ca

Abstract

Micro energy grids (MEG) have been proposed to fulfil the concurrent expansion of electrical, cooling and heating energy distribution systems, without taking in consideration safety performance indices. This study is concern on risk analysis of micro energy grids (MEG) with corresponding uncertainties in electrical, cooling and thermal demands; further to the impact of PV and wind power productions intermittency. Several contributions are presented in this paper, such as: developed hazard matrix of MEG, developed two approaches of risk assessment, i.e. fault tree analysis and layer of protection analysis (LOPA), and finally proposed a solution to prevent and mitigate the hazard impacts by offering a resilient MEG configuration model. This model consists of an enhanced independent protection layers (IPL)s, i.e. Co-generation, thermal energy storage (TES) and multi-level hierarchical control. The performance of the proposed configuration model has proven that it reduces the influence of the renewable sources intermittency and also increases the MEG production capacity. Also the proposed model shows a robust self-healing capability, to meet on-demand load requirements, under different hazardous scenarios. Further to achieve the simultaneous goals of increasing the energy efficiency, reducing gases emission and improve sustainable economics.

Keywords: *Micro Energy Grid (MEG); Fault tree analysis; Layer of protection analysis (LOPA); Independent Protection Layers (IPL); Resiliency, Reliability, Fuzzy Control system; Hierarchical Control System; Fault Tolerant Control.*

1. Introduction

With the increasing concerns regarding energy reliability and emissions, the claim on self-generation and distributed energy resources (DER)s are increasing accordingly. Two-thirds of all fuel used to produce power electricity is mostly wasted by emitting unused thermal energy from power generation system into the air or into water streams (e.g. sea and river). The average efficiency of power generation has remained around 33 percent since 1960. A combination of electric power generators, district cooling/heating units, energy storage devices, and renewable energy sources are widely deployed to meet the energy demands of electrical, cooling and heating for several types of buildings [1]. This combination is commonly named micro energy grid (MEG). MEG can increase the overall energy efficiency of an energy system further to provide environment benefits by reducing primary energy consumption and related greenhouse gas emissions [2]. These systems can upsurge the energy efficiency up to 90 percent, by utilizing thermal energy produced as a by-product of power generation for cooling, heating, and humidity control systems [3][4]. Thus, implementing of such a large complex system with uncertainty of dealing with various unknown parameters is increasing the hazardous condition [5]. Consequently, the hazard analysis is a critical part of system safety design. Where safety design of MEG having higher fault tolerance ability against various types of risks events and hazardous scenarios is paramount for resilient MEG. The resilient MEG is a small or medium scale autonomous energy supply system which is merged of smart meters and sensors, automated controls and advanced software. The advanced software employs a real-time distribution data to detect and isolate faults by reconfiguring the energy flow to minimize the customer's impact and to increase the system self-healing capability. This simultaneous goals requires a continuous optimization and dispatch of resources. Distinctly, MEG should cover requirements of all the three types of energy (electrical power, heating, and cooling). The gas generator (GG) generates electricity to cover the electrical load demand with the exhaust heat as a by-product [6]. Utilizing a heat recovery steam generator (HRSG) enabling to restore the exhaust heat produced by the plant generators, where co-generation mainly covers the associated intermittency and non-coincidence of on-site renewable resources. Thermal energy storage system (TES) provides flexibility to 'reform' the cooling demands during the course of a day, to improve the system resiliency against the risk of loss of one district cooling units or transient increase of cooling demand. Another TES with an auxiliary boiler are generally used in order to meet the heating demand. The proposed modelling and predictive control approach aims to design a managerial fault tolerant control strategy to optimize those potentials efficiently. In addition, a risk analysis techniques were used over multiple physical domains of MEG system spans to evaluate the improvement on the proposed system.

2. Proposed MEG Design and Modelling

Fig.1 shows the resilient MEG model including all the independent protection layers proposed to increase the self-healing capability which will be discussed later in this paper. The proposed MEG configuration able to perform with self-reliance of its power loads, cooling load and heating loads most of the year by employing gas generator (GG), wind turbine farm (WT), photo-voltaic power (PV), heat recovery steam generator (HRSG), and chiller units (CU) with thermal energy storage (TES)[7]. Despite the MEG has the ability of operating in islanded mode, it is interconnected with the capital grid to ensure resilience operation during hazard scenarios and to offer backup sources for uncertainty of increasing demands. A set of 6 electric chiller units of a similar performance features and capacity, shown in Table 1, produces cold water to supply the cooling loads, and to store surplus cooling energy in a TES tank of 500 MWh capacity. A co-generation gas turbine (GG) of 15 MW rate is the essential source of electricity in the proposed configuration model. The exhaust gases of GG can generate steam by using HRSG. The steam drives a 3 MW steam turbine in order to produce additional electricity, and to produce heat energy to cover majority of the facility heating loads [8]. Hence, the detailed mathematical model of MEG components were discussed extensively in [6].

3. Hazard and Risk Analysis Techniques in MEG

As foundation design does not consist of inherent safeguard protection layers, Table 2 shows the major hazards which threaten the MEG system in electrical, cooling and heating grids additionally it identifies the possible remedies to overcome the related consequences such as the risk of failure or blackout.

Hazard level can be calculated by the following formula [9]:

$$Hazard\ Level\ (H_L) = S_i * C_i \qquad (3\text{-}1)$$
$$C_i = (P_i + F_i + A_i)$$

Where S_i: consequence severity of the hazard event, C_i: is the class hazard event likelihood, P_i: probability, F_i: frequency and A_i: the ability for failure avoidance.

Each row in hazard matrix, shown in table 2, defines certain hazard. It consists of a hazard event, the frequency and probability of event's occurrence, the avoidance of the event, the severity of hazard event's consequences and proposes a (mitigation and prevention) actions for hazard event. The frequency, probability and avoidance parameters of the hazard occurrence can be illustrated from historical data or assessed based on professional judgement.

3.1 Hazards of Electrical MEG

The following points can summaries the main hazard events in Electrical MEG

1- Over load (above the grid Capability): electrical demand can suddenly increase for limited period of time due to different factors such as extremely hot or cold weather which may lead to several negative impacts:

I. Impacts on human: demand not served (DNS)
II. Impact on facility: overheated transmission and distribution cables, Asset Damages, fire and power blackout.
III. Impacts on environment: fire causes CO_2 emission

This can be prevented by several remedial actions and/or IPLs such as:

- Upgrade grid capacity, which cost time and money
- Shift on-peak power demand, by using Intelligent Energy Storage System such as super capacitor, Fly Wheel, TES and pumped hydro, or hydrogen storage.
- Dynamic grid mapping based on load demands and priorities

2- Lack of DER at MEG: DER can be out of service due to routine maintenance or due to system breakdown or failure. The negative impact could be as follows:

I. On human: interruption on service
II. On facility: could lead to risk of losing the electricity power for wide region or general blackout.
III. On environment: lack of DER means increase the demand on fossil fuel generators which cause dramatic increase of the emission.

Preventing IPL action can be achieved through high dynamic performance of the distributed power and energy system by:

- Store off-peak power production for using at emergency or on-peak demand
- Utilize Co-Generator
- Connect to Capital Grid (Utility)

3- Utilize of on-site renewable sources: despite of renewable resources is known as eco-friendly energy source, it has accompanying hazard of intermittency and non-coincidence at energy production which led to lack on providing the required power demand. This can be prevented by utilizing the IPLs mentioned in point 2.

4- Integration of multi sources DERs: has Negative impacts on grid parameters such as active power (P), reactive power (Q), voltage (V), phase shift (α) and frequency (f). Remedial action and IPL as following:

- Full utilization of DERs to increase energy efficiency
- Improve power quality
- Enhance system stability

3.2 Hazards of Cooling MEG

Cooling MEG resiliency is affected by the following hazards:

1- High correlation between cooling demand and electricity demand: this relation has negative effects on the MEG resiliency as follows:

I. Impacts on human: uncomfortable condition (temperature & humidity)
II. Impacts on facility: the on-peak demand for both electricity and cooling grids accrued at the same time and this subsequently lead to increase the actual electricity on-peak demand which might cause interruption and/or blackout for both services.

III. Impacts on environment: Increases the demand on Fossil Fuel generation and its consequences on emission

This hazard can be avoided by Shift on-peak cooling demand to off-peak demand by TES utilization and intelligent management control.

2- MEG contingency with lack of Chiller unit: this might cause inability to meet the cooling on-peak demand which has undesirable influences as follows:

I. Impacts on human: uncomfortable condition due to DNS
II. Impacts on facility: shortage on cooling production lead to lack on service
III. Impacts on environment: individual A/C units is one of the solution to overcome the lack of service and A/C unit usage has impact on electricity demand and global warming.

This hazard can be evaded by store off-peak cooling production for using at on-peak demand using TES and management control to ensure higher MEG reliability level

3.3 Thermal Heating MEG Hazards

From the historical data for heating demand it can be clearly defined that it has irregular heating demand also it has low correlation with electrical demand which might led to hazard of failure on meeting the on-peak heating demand. The consequence of the failure has several negative impacts:

I. Impacts on human: uncomfortable condition (temperature & humidity).
II. Impacts on facility: failure to meet the heating on-peak demand
III. Impacts on environment: increases the requirement for alternative heat sources such as furnace which is increase the gases emission

To prevent the hazard of heating failure a strategy to store off-peak heating production should be utilized in order to be when required at on-peak demand

3.4 Transportation MEG Hazards

Transportation is vital service for the society and the public therefore the energy demand conjugated with it is essential for its resiliency. Any interruption might have harmful impacts:

I. Impacts on human: fatality, injury and delay.
II. Impact on facility: failure in energy threaten the safety for properties and the public.
III. Impacts on environment: back-up Engines works using fossil fuel which increase the emissions.

Achieving energy management balance between transportation units and MEG is one of the main solution for more reliability, security enhancement, emissions reduction and energy quality improvement.

4. Safety Design and Protection Layers for MEG

Safety design for the MEG is aimed to improve the stability for the energy system during abnormal conditions and to prevent faults and damages propagation. This can be achieved by interrupting and isolating faulted or failed components from the system, as well as to provide safety strategies for properties and the public safeguards [9].

The dynamic structure of the MEG and their various operating conditions required the development of adaptive protection strategies using intelligent control and monitoring unit based on safety design criteria.

The ANSI/ISA-84.00.01-2004 (IEC 61511) standard defines a safety instrumented system (SIS) as an instrumented system used to implement one or more safety instrumented functions. A SIS is a combination of sensor(s), logic solver(s), and final element(s). IEC 61508 uses the term "safety-related system" instead of uses the term SIS. This term describes the same principle but with different language context that can be broadly applied to many industries [10].

The main purpose of a control loop, in a basic process control system (BPCS) is generally to maintain a process parameter within prescribed limits. A SIS monitors a process parameters and interfere when required [11].

Risk analysis teams generally assess the hazardous situations that occur during the operation stream. The average time period between hazardous events is commonly evaluated to be over 10 years when the process design is successfully oriented toward safety. In consequence, the SIS is might activated only once every ten years or more in some cases and it is passive during normal operation. A chart of SIS operating conditions is shown in Table 3. The essential problem is the fail-danger mode. Hence, the process is operating normally under this condition but without the automatic protection of the SIS and without indication that something has failed [12].

4.1 Independent Protection Layers

Independent protection layer (IPL) can be defined as a device, system, or action has the capability of preventing a scenario from proceeding to its undesired consequence independent from the initiating event or the action of any other layer of protection associated with the scenario. The main characteristics of IPL are:

- Its ability in blocking fault's consequence when IPL functions as designed
- Should be auditable where the assumed effectiveness in terms of consequence prevention and PFD (Probability of Failure on Demand) must be capable of validation (by documentation, review, testing, etc.)

Layer of protection analysis (LOPA) is utilized to determine if sufficient IPLs can tolerate the risk and suppress the consequences of an accident scenario to an acceptable level [13]. Each IPL has its own probability of failure on demand (PFD)

$$\boldsymbol{PFD = p_n \ , where\ n\text{: } indicate\ layer\ level} \quad (4\text{-}1)$$

PDF value has direct impact on system resiliency as declared on LOPA path equation:

$$\boldsymbol{LOPA\ path = f_n} = \left(\prod_{\boldsymbol{i=1}}^{\boldsymbol{i=n-1}} \boldsymbol{p_i}\right) * \boldsymbol{f_0} \quad (4\text{-}2)$$

Fig. 6 shows the proposed IPL layers required to tolerate the hazard of losing energy dispatch for MEG system, where co-generators, Thermal energy storage (TES), and supervisory fault tolerant energy management control utilized to achieve the simultaneous goals of energy dispatch resiliency, self-healing capability, and energy production quality, cost and emissions

I. IPL-1 Co-generators: such as fuel cells, micro-gas turbines, and hybrid turbine systems are able to cover the lack of power demand and to respond to renewable interruptions

II. IPL-2 Thermal energy storage: is an effective solution for MEG applications due to the listed below points:

A- Centralized infrastructure where large thermal reservoirs provide flexibility to manage cooling and/or heating dynamics as well as lower emissions and energy failure risks

B- Shift on-peak production demand to off-peak hours in order to mitigate congested demand subsequent hazards

III. IPL-3 a hierarchical control system: for efficient management of MEG's components and to reduce the negative impact of the renewable energy source and MEG overall operation. IPL3 is seen as the most effective means for increasing the MEG self-healing ability.

Different types of IPLs can be utilized to increase MEG resiliency are shown in Table 1, and can be summarized as follows:

a. MEG Storage system (E/T/C)

b. Intelligent control system at normal operation to ensure rigid performance
c. Smart energy asset management for both sources and load within MEG boundary
d. Emergency control for resilient system on abnormal cases
e. Risk assessment platform
f. MEG safety shutoff and restoration system

These IPLs can be implemented and studied on later researches for performance comparison between different techniques on the MEG resiliency and to enhance MEG self-healing characteristics.

4.2 Fault Tree for the MEG

In reliability engineering, the primary statistical variable of interest is Time to Failure (T). The time to failure measurement can be analyzed to generate another important measurement, failure rate. Instantaneous failure rate is a commonly used measure of reliability that gives the number of failures per unit time from a quantity of components exposed to failure.

$$\boldsymbol{\lambda(t) = Failure\ Rate = Failures\ per\ Unit\ Time/Quantity\ Exposed} \qquad (4\text{-}3)$$

$$R(t) = e^{-\lambda t}$$
$$F(t) = 1 - e^{-\lambda t} \approx \lambda t$$
$$MTTF = 1/\lambda$$

Fault tree is a common technique to illustrate probability combinations. This technique begins with the definition of an "undesirable event," usually a system failure of some type. The analyst continues by identifying all events and combinations of events that result in the identified undesirable event. The fault tree is therefore quite useful when modeling failures in a specific failure mode. These different failure modes can be identified as different undesirable events in different fault trees. Fig. 7 shows a top event which defined as probability of failure on demand (PFD) for a proposed MEG safety instrumented function. This method provides a clear way to express the reality of multiple failure modes. And the PFD for a MEG can be estimated by using the following equation:

$$\boldsymbol{F(MEG) = F(Capital\ Grid) * F(Distribution\ Energy) = [F(Capital\ Grid) + F(Chiller) + F(MT)] + [(F(Co-gen) * F(Renw)) + (F(Co-gen) * F(TES)) + (F(Co-gen) * F(Manag)) + (F(Renw) * F(TES)) + (F(Renew) * F(Manag)) + F(TES)]} \qquad (4\text{-}4)$$

Where the PFD for the individual systems can be illustrated from historical database and experience. Individual PDF were demonstrated in table 4 and table 5.

Compensation of individual failure rate for each device in equation (4-2) illustrates that the probability of energy blackout for the MEG was reduced 9 times by utilizing a proposed IPLs and distribution energy sources where the PFD became $78.7e^{-3}$ while it was $649.2e^{-3}$ for the conventional energy grid.

In the same way LOPA shows reduction on system risk level from 0.4893, SIL-1, for the conventional energy grid [14][17] to $1.611e^{-6}$, less than SIL-4, with the proposed IPLs, fig. 8 shows the LOPA diagram and calculation for the proposed IPLs.

Where LOPA path can be defined using equation (4-2); LPOA= f_3= $0.1991*0.1647*0.05*0.001=1.611e^{-6}$

4.3 Multi-level hierarchical control of MEG

A multi-level hierarchical control (MLHC) is one of the IPLs proposed in this paper. It enhanced the self-healing characteristics of MEG, against uncertainty hazards, during system operation. The structural design of MLHC consists of three simultaneous levels functioning together to attain resilient operation.

4.3.1 Hierarchical control architecture

A hierarchical control design is offered and applied in order to manage the energy resources efficiently and effectively utilizes the MEG components. It comprises of three levels, including a self-ruling decision making level, a predictive control level, and a reactive control level. Each level has its own local objective and they work together to realize a resilient operational performance. The higher level controller involves a fault tolerant control formulation, in order to deal with uncertainty hazardous conditions and to determine the best action for each subsystem. The predictive control level harnesses a prescheduled operational timing to manipulate the chiller units (CU) operation. The predictive control aims to operate the CU units at off demand timing for charging the TES which required to cover an on-demand peak period. The lower level controller is a load following control for the demand which needs fast response. Fig. 9 shows the hierarchical control architecture.

The quality of any control depends on the assumed information and control structures [18]. A central decision maker defines values of control based on obtainable information collected from all subsystems. Nevertheless, a centralized method might be difficult to realize in large scale systems, where a process of transmission and transformation of information are more complicated. Decentralization of information and control structures is a feasible solution to overcome this dilemma. Control problems with decentralized measurement information are the main element for the hierarchical control. A decomposition of a large system into subsystems is mainly aimed to minimize the required computations further to reduce the amount of information required for a decision making level [19].

In the past the MEG was classified either islanded or grid-connected approaches. While, it is essential for resilient energy system to modify a flexible MEG able to operate in both grid-connected and islanded modes [20]. This system is open the door for great challenges, where establishing this system requires of integrating different technologies of energy sources, energy storage, and energy management systems. In addition to, safety issues such as fault monitoring, predictive maintenance, or protection which are fundamental principles for a MEG with high level of self-healing capability.

This paper is concentrate on the decision making and predictive control levels to manage the cooling demand and to minimize its negative impacts on the electrical energy system. Fuzzy (sugeno) rules were implements for softening the conflict between prescheduled chiller units (CU) operation and reactive control response.

4.3.2 Fuzzy decision making method

The fuzzy method is considered as a simple and tangible approach for solving dynamic nonlinear systems. Sugeno or Takagi-Sugeno-Kang fuzzy system was proposed in this paper for its ability to provide a systematic method for producing fuzzy rules for a definite input/output streams. The main difference between mamdani and sugeno is that the sugeno output membership functions are either linear or constant. eq. (4 5) shows the typical rule in sugeno fuzzy model [21].

$$\boldsymbol{If\ Input\ 1\ =\ x\ and\ Input\ 2\ =\ y, then\ Output\ is\ z\ =\ ax\ +\ by\ +\ c} \tag{4-5}$$

The final output of fuzzy system is the weighted average of all rule outputs output of the system is the weighted average of all rule outputs, computed as

$$\boldsymbol{Final\ Output = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i}} \tag{4-6}$$

Where z_i output for each rule and w_i is the weight

4.3.3 Electrical and Cooling Energy System Procedure

Fig. 10 and fig. 11 are summarize the general procedure for both cooling and electrical systems at a resilient MEG , note that the heating system was not mentioned due in this section because the heating demand are covered by the excessive heating energy produced by co-generator and HRSG.

5. Case Study Scenarios and Discussions

5.1 Simulation Scenarios

To validate the dynamic behaviour of the MEG system which employ different levels of independent protection layers, mentioned in Section 4.1 , a case study for the proposed resilient MEG system is presented in this section using the Simulink environment. Fig. 12 shows proposed resilient MEG has three IPLs including a hierarchical control system. The proposed MEG system is implemented in the Simulink environment platform to study the system performance in different operational scenarios in order to examine the MEG system resiliency for prescribed cooling, heating and electricity energy demands.

Studying the following scenarios can realize a clear vision about the IPL performance and MEG resiliency:

Scenario-1: Study operation and performance of MEG (with co-generation)
IPL-1 was applied in order to define the improvement level of MEG resiliency due to interconnect the gas generator to eliminate the renewable resources penetration and to cover around 60% of the energy demand requirements. In other words, this means a reduction of the severity risk of energy failure to 60% of the capital grid total failure.
Scenario-2: Study operation and performance of MEG (with TES and co-generation)
To define IPL-2 capability on MEG self-healing by partially shifting the energy demand from on-peak period to other off-peak timing, it can be shown that it safeguards more than 17% of the total energy demand
Scenario-3: Study operation and performance of MEG with TES, co-generation and a hierarchical control system)
IPL-1, IPL-2 and IPL-3 were provided to the MEG in order to increase its capability and operate in islanded mode which means IPL-3 is providing the remainder of the 23% of the total energy demand by applying a hierarchical control technique for a MEG system.

5.2 Results and discussion

In order to assess and evolve the MEG system operation a data for one week in summer has been studied carefully. The interaction between co-generators, district cooling unit, TES storage, and the capital power grid are explored to increase safety, resiliency, and self-healing for MEG system. three scenarios were examined in this section.

- Scenario-1, one IPL, co-generation, was utilized
- Scenario-2, two potentially valuable structures, that is, the TES and cogeneration are used.
- Scenario-3, all the three IPLs proposed in this paper were used

The objective of the proposed strategy is to verify the performance of the proposed resilient MEG system by utilizing a hierarchical control system with TES and Co-gen for optimal shifting of the cooling demand to off-peak hours. Hence, to study its effects on the safety design able to reduce hazardous scenarios of system failure. Measurements of MEG generation, capital's power imports, and thermal cooling units operation have been processed for optimum management of the electricity, heating and cooling energy demands.

5.2.1 Scenario-1 Foundation MEG design with co-generation

Fig. 13 illustrate the power demand profile for one week in summer for foundation MEG system without inherent of the proposed IPLs. The figure clearly defined that the combination of co-generator and renewable sources can't handle the power demand alone therefore the capital power is required to cover the power deficiency caused by sudden raise on the power demand. The power deficiency caused by two reasons, first due to limited capacity of DERs and secondly due to the dynamic behaviour of co-generator which led to delay respond to rapid change on the demand profile.

Cooling profile in fig. 14 shows the MEG cooling demand within one week in summer without utilizing co-generator and TES, the figure illustrates a high frequency of on- off chiller units (CU) operation during a course of the day. This leads to dramatically increase on the inrush current during CU units' start-up which might cross beyond a double of the chiller rated current. On other hand CUs are in duty most of the day with an increasing number of operated units during on-demand period. Keep in consideration the fact of high correlation for cooling demand with electricity.

5.2.2 Scenario-3 Resilient MEG design comprises TES and cogeneration IPLs

Fig.15 presents a sample of the resulting power demand profile for one week in summer using co-generator and TES IPLs only. The above figure defined clearly that the co-generator with supports of renewable power sources can't cover all the power demand during the course of the day where the capital grid power is partially required to cover the deficiency caused by sudden raise on the power demand. The power deficiency occurred two to four hours a day with maximum 8 MW while co-generator serves an average of 14 MW with maximum production capacity of 18 MW.

Cooling profile in fig.16 shows the MEG cooling demand within one week in summer while co-generator and TES were utilized, the figure also illustrate that the TES improves the cooling production with less operational hours for the thermal cooling units. However, the fact of high correlation for cooling demand with electricity demand.

Fig.17 presents a sample of the heating demand profile for one week in summer. The figure shows extensive coverage of heating demand by the heat generated by the co-generator unit. Furthermore, there is a comparatively low correlation between electrical demand and heating demand, particularly during the summer season.

5.2.3 Scenario-3 Resilient MEG design comprises three IPLs

Using the three IPLs have impressive improvement on the safety of a MEG system. Furthermore, it is reducing the necessity for capital grid imports. Fig. 18 shows more smooth power profile from capital grid. The deficiency between total power demand and DERs production occurred on the first two days for a period of one hour in each. Mainly this happen due to charging schedule for the TES during night. It can be clearly noticed that the proposed system succeeds on shifting the cooling demand power requirement to off-demand period. The power deficiency occurred at midnight with maximum 4 MW.

The cooling profile in fig. 19 shows an improvement in the thermal cooling units operations, where cooling on demand was shifted completely to the off demand period, by using a hierarchical control and reschedule the operation of the district cooling units. The shifting of cooling on demand has major positive impact on both power and cooling profiles, subsequently it is increasing the MEG capability without additional physical hardware upgrade for the MEG system, further to the increase on the MEG resiliency and self-healing competency.

Fig. 20 below shows the fuzzy controller construction and fuzzy members discussed in section 4.3.2 .

A trial of the heating demand profile for one week in summer was presented in fig. 21. Widespread coverage of the heating demand can be achieved by the heat generated from the co-generator unit. However, the figure demonstrate that the heat generated by co-generators is excessive with respect to the heating demand on summer.

6. Conclusions

In this paper a hazard analysis approach was developed to study and evaluate the safety performance of MEG. Also safety design for MEG system was proposed and validated using Simulink platform environment. The aim of this study is to create a resilient MEG has the ability to mitigate major hazards threaten the current MEG. Three independent protection layers (IPLs) were offered to achieve this desired goal. A combination of gas-generator, TES and a hierarchical control system are used to increase the reliability of MEG and to minimize the dependency on capital grid during all seasons. Those IPLs reduce the probability of energy blackout for a resilient MEG with more than 9 times as well as doubles the capacity of MEG, by increasing the safety margin between energy sources availability and the energy demands. The combined configuration of gas-generator, TES and a hierarchical control system offers a significant reduction on the capital grid risk severity, as shown in section 4.2. IPLs improves MEG performance with practical everyday considerations such as equipment maintenance and variation in energy demand that affect the MEG operation and the load distribution. Predicting future load profiles from historical data can provide tolerable approximates in scheduling the dispatch of the MEG resources, which can be easily adapted using the real-time energy dispatch control for effective management of the MEG resources and energy flow mapping.

References:

[1] H. Gabbar, "Design and Planning Support Tool for Interconnected Micro Energy Grids," *Br. J. Appl. Sci. Technol.*, vol. 12, no. 6, pp. 1–15, 2016.

[2] Z. Zhou, P. Liu, Z. Li, E. N. Pistikopoulos, and M. C. Georgiadis, "Impacts of equipment off-design characteristics on the optimal design and operation of combined cooling, heating and power systems," *Comput. Chem. Eng.*, vol. 48, pp. 40–47, Jan. 2013.

[3] M. Meckler, *Sustainable on-site CHP systems : design, construction, and operations /*. New York : McGraw-Hill, 2010.

[4] M. Liu, "Energy Efficient Operation Strategy Design for the Combined Cooling, Heating and Power System," University of Victoria, 2012.

[5] A. Chaves and A. Terry Bahill, "Comparison of risk analysis approaches and a case study of the risk of incorporating solar photovoltaic systems into a commercial electric power grid," *Syst. Eng.*, vol. 17, no. 1, pp. 89–111, 2014.

[6] H. A. Gabbar and Y. Koraz, "Safety Design of Resilient Micro Energy Grids," in *Smart Energy Grid Engineering*, 1st ed., Elsevier/Academic Press, 2017, pp. 101–150.

[7] Y. Koraz and H. A. Gabbar, "Hierarchical Safety Control for Micro Energy Grids using adaptive neuro-fuzzy decision making method," in *IEEE International conference on Smart Energy Grid Engineering*, 2016, pp. 131–136.

[8] V. Chandan *et al.*, "Modeling and optimization of a combined cooling, heating and power plant system," in *2012 American Control Conference (ACC)*, 2012, pp. 3069–3074.

[9] D. K. Pradhan, J. Mathew, and R. Shafik, *Energy- Efficient Fault-Tolerant Systems*. New York :

Springer Publishing Company, Incorporated, 2014.

[10] W. M. Goble and H. Cheddie, *Safety Instrumented Systems Verification: Practical Probabilistic Calculations*. 67 Alexander Drive P.O. Box 12277 Research Triangle Park, NC 27709: ISA-The Instrumentation, Systems, and Automation Society, 2005.

[11] K. Wolter, “Stochastic Models for Fault Tolerance: Restart, Rejuvenation and Checkpointing,” Jun. 2010.

[12] E. Dubrova, “Fault-tolerant design,” 2013.

[13] M. R. Islam and H. A. Gabbar, “Study of Micro Grid Safety & Protection Strategies with Control System Infrastructures,” *Smart Grid Renew. Energy*, vol. 3, no. 1, pp. 1–9, Feb. 2012.

[14] H. Danesh, K.-Z. H., H. Daneshi, H. Khorashadi-Zadeh, H. Danesh, and K.-Z. H., “Microgrid Energy Management System : A Study of Reliability and Economic Issues,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–5.

[15] N. Petchers, *Combined Heating, Cooling & Power Handbook: Technologies & Applications an Integrated Approach to Energy Resource Optimization*. Fairmont Press, 2012.

[16] eeh power systems laboratory, “UCTE system adequacy forecast,” 2007.

[17] A. R. Abbasi and A. R. Seifi, “Considering cost and reliability in electrical and thermal distribution networks reinforcement planning,” *Energy*, vol. 84, pp. 25–35, 2015.

[18] Y. Li and D. Mavris, “A Hierarchical Control Architecture for Resource Allocation,” vol. 2012, no. December, pp. 5–7, 2012.

[19] Z. Duda, “TWO-LEVEL HIERARCHICAL CONTROL IN A LARGE SCALE STOCHASTIC SYSTEM,” in *Proceedings of the European Control Conference*, 2001, pp. 2193–2197.

[20] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, 2011.

[21] M. Kurano, M. Yasuda, J. Nakagami, and Y. Yoshida, “A fuzzy approach to Markov decision processes with uncertain transition probabilities,” *Fuzzy Sets Syst.*, vol. 157, no. 19, pp. 2674–2682, 2006.

[22] Aras Sheikhi, Mohammad Rayati, Ali Mohammad, Demand side management for a residential customer in multi-energy Sustainable Cities and Society, Volume 22, April 2016, Pages 63-77

[23] Shintaro Ikeda, Ryozo Ooka, Optimal operation of energy systems including energy storage equipment under different connections and electricity, Sustainable Cities and Society, Volume 21, February 2016, Pages 1-11.

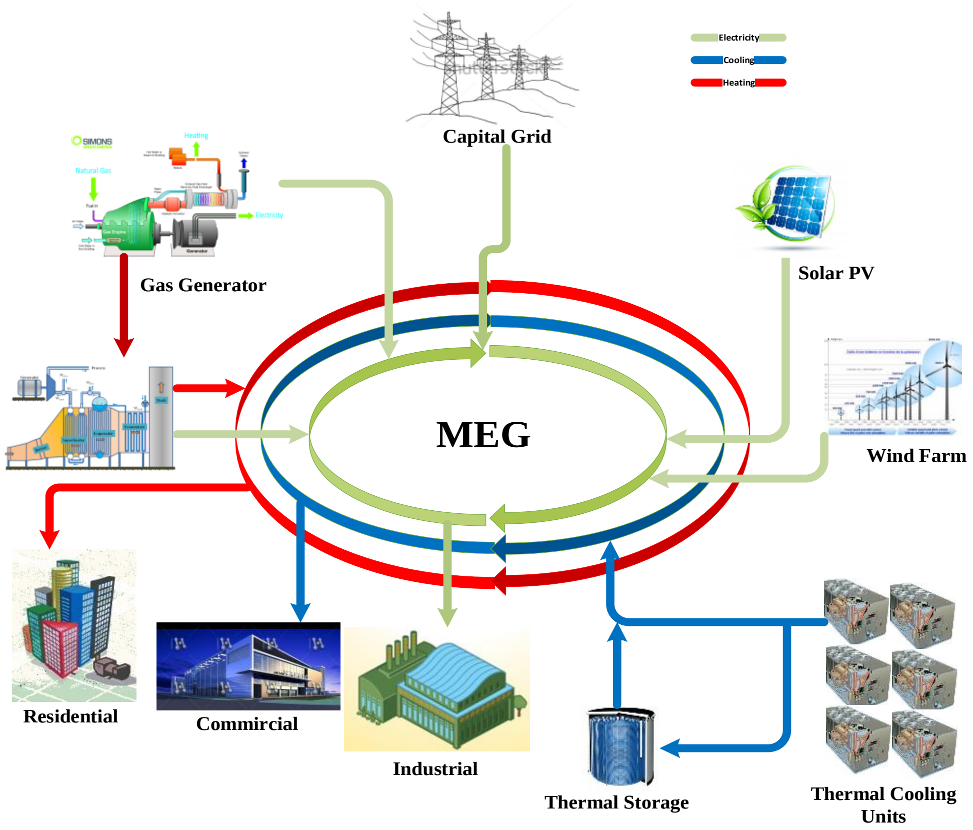


Fig. 1: Proposed MEG Configuration Model

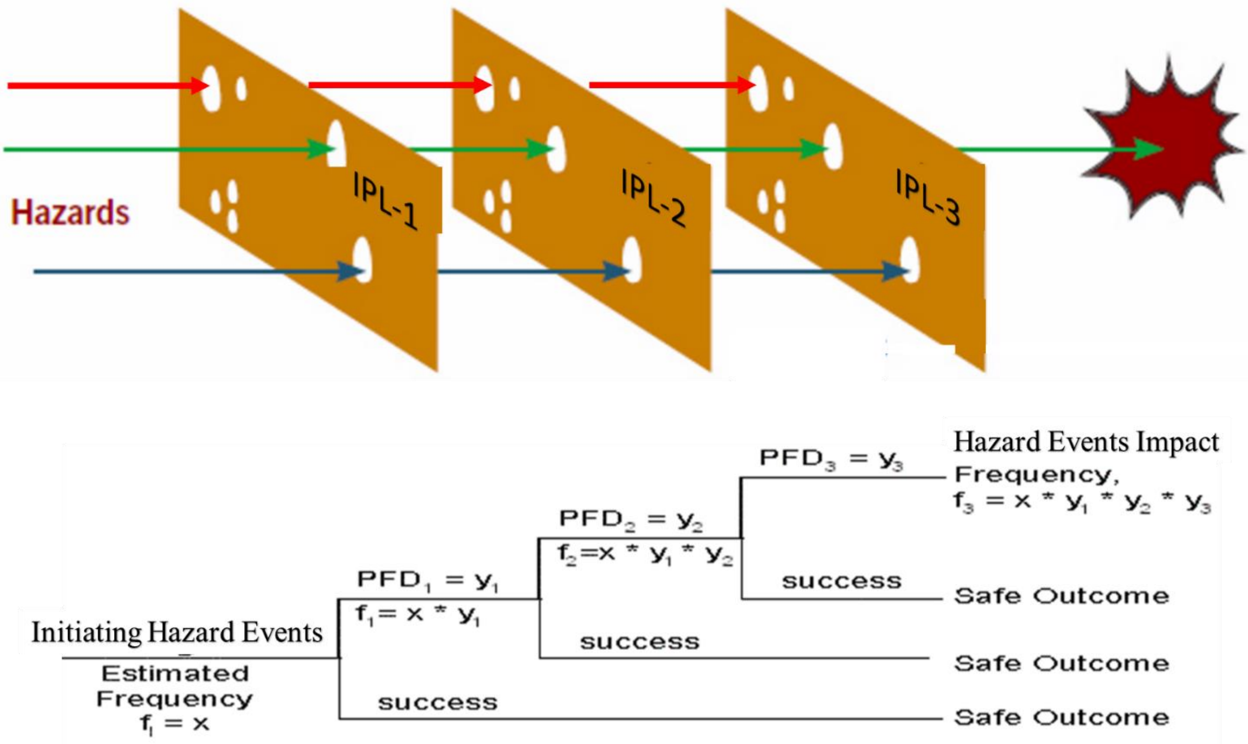


Fig. 6: Path diagram for the MEG system

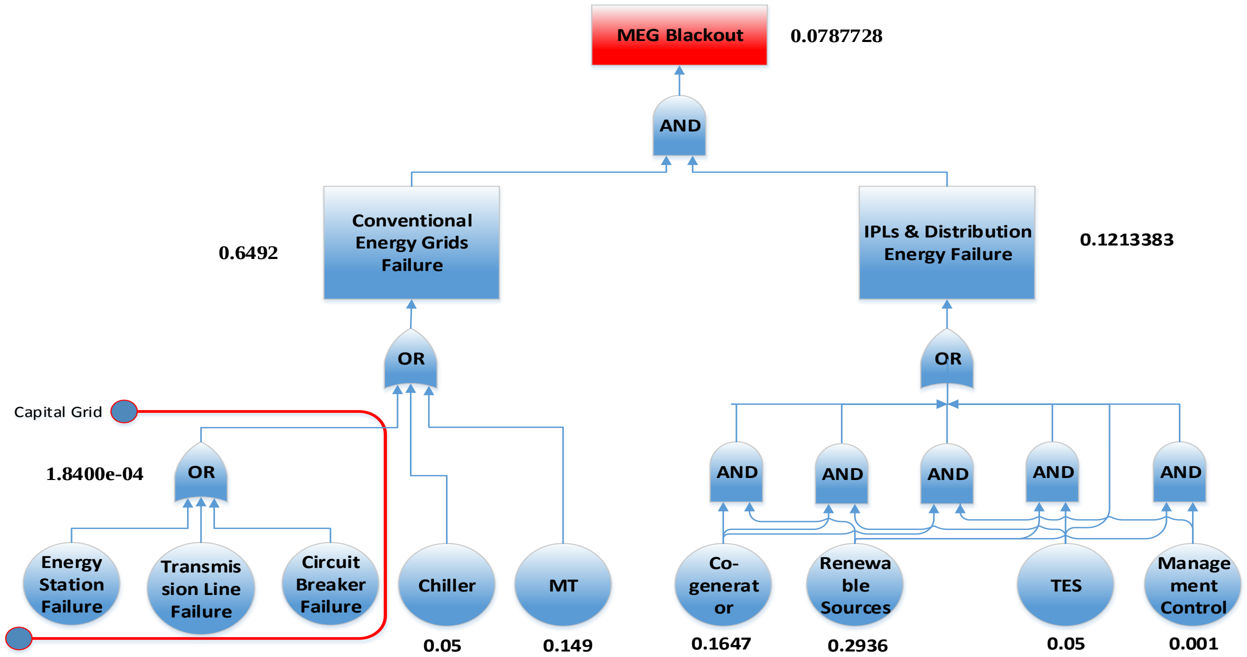


Fig. 7: A MEG fault tree

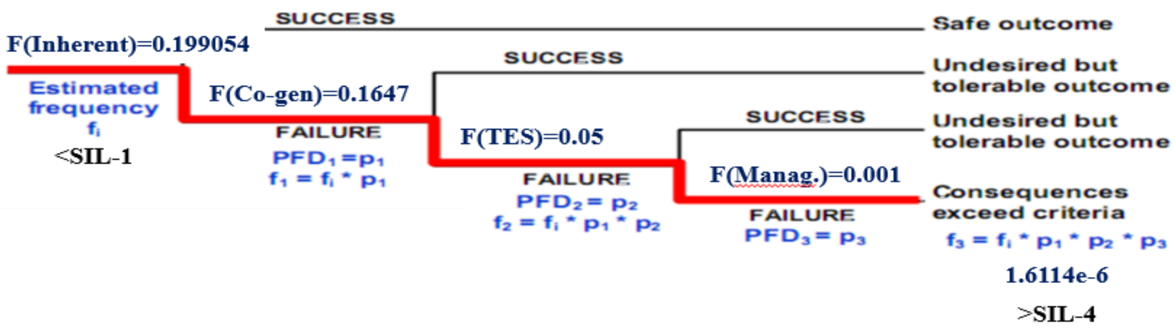


Fig. 8: LPOA diagram for the proposed resilient MEG

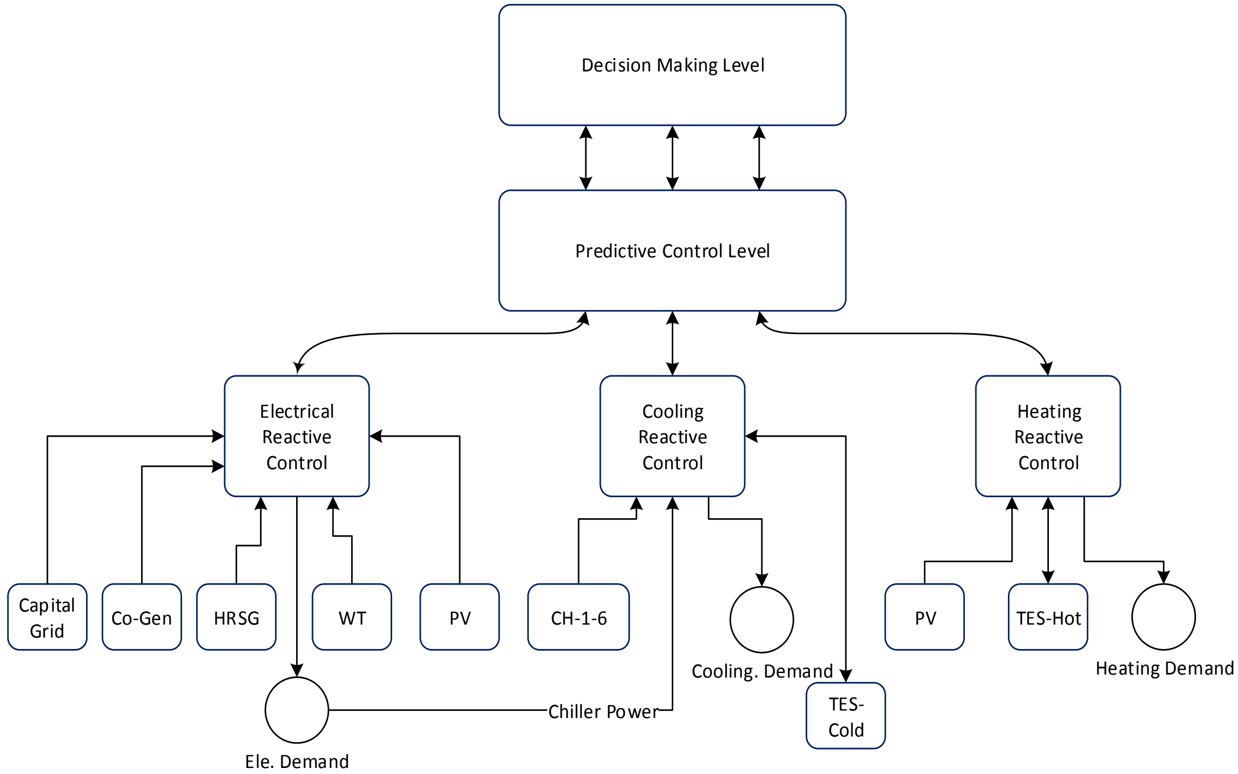


Fig. 9: Hierarchical control architecture for MEG

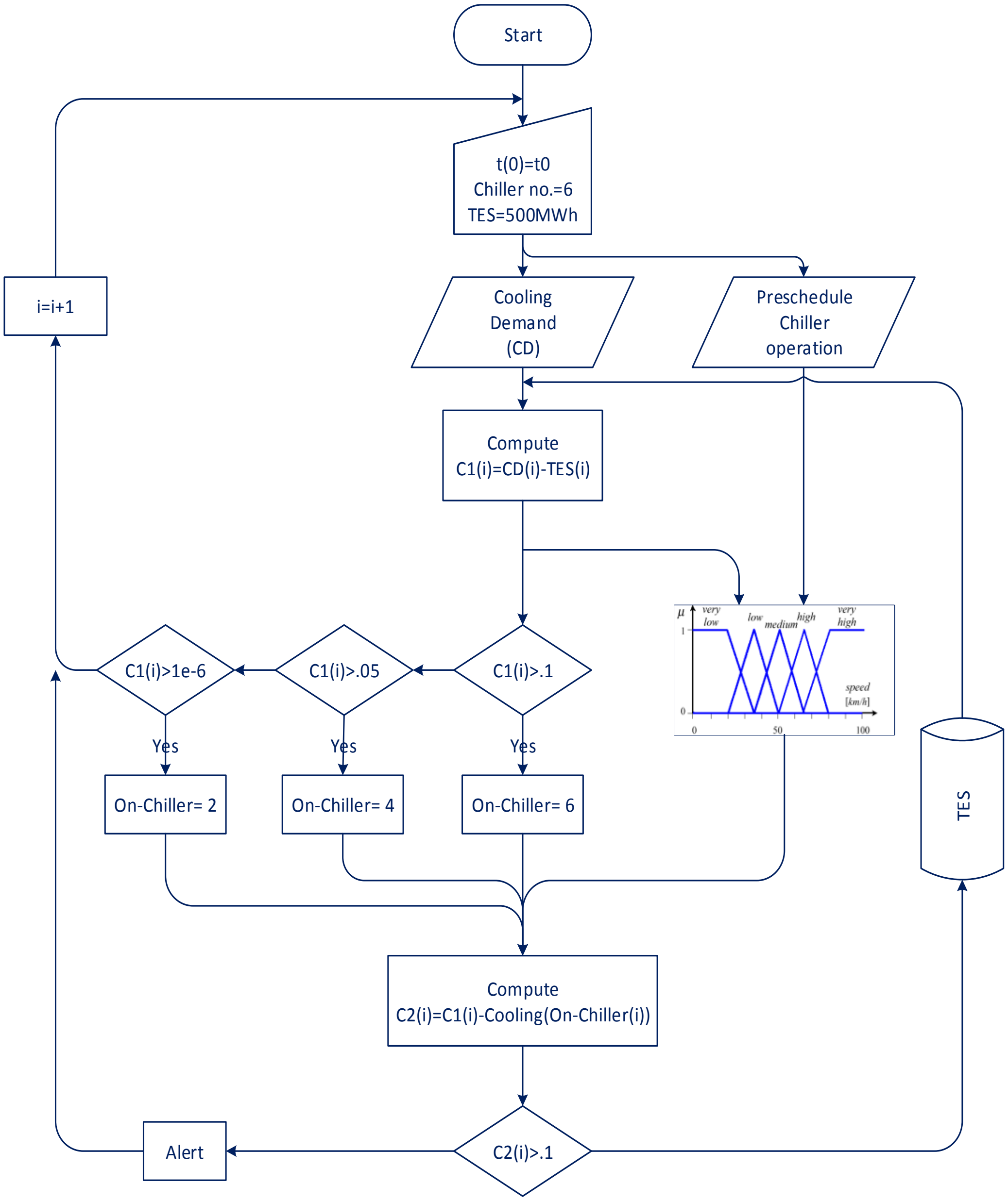


Fig. 10: The MEG Cooling System Flowchart

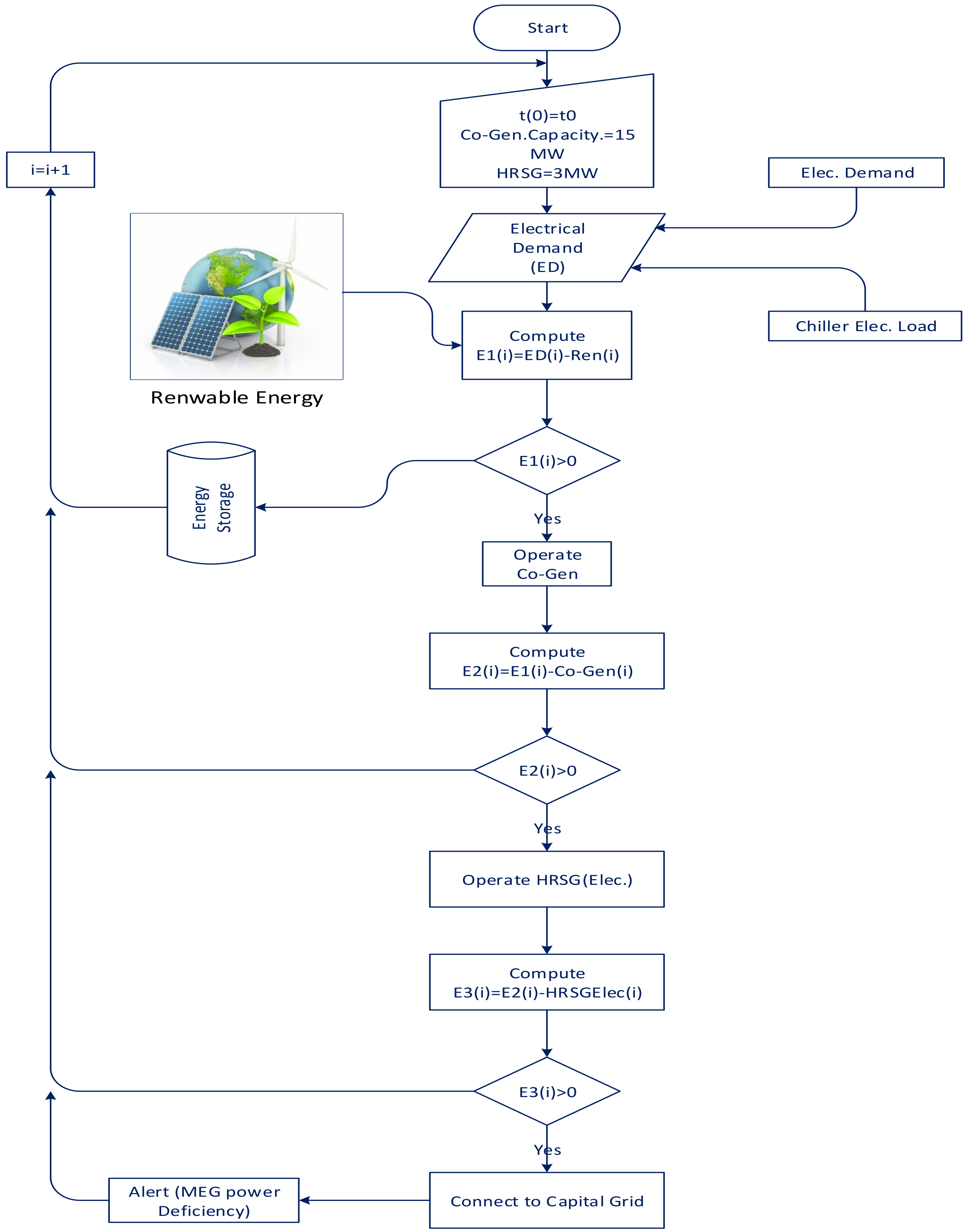

Start
t(0)=t0
Co-Gen.Capacity.=15
MW
HRSG=3MW
i=i+1
Elec. Demand
Electrical
Demand
(ED)
Chiller Elec. Load
Compute
E1(i)=ED(i)-Ren(i)
Renwable Energy
E1(i)>0
Energy
Storage
Yes
Operate
Co-Gen
Compute
E2(i)=E1(i)-Co-Gen(i)
E2(i)>0
Yes
Operate HRSG(Elec.)
Compute
E3(i)=E2(i)-HRSGElec(i)
E3(i)>0
Yes
Alert (MEG power
Deficiency)
Connect to Capital Grid

Fig. 11: The MEG Electrical System Flowchart

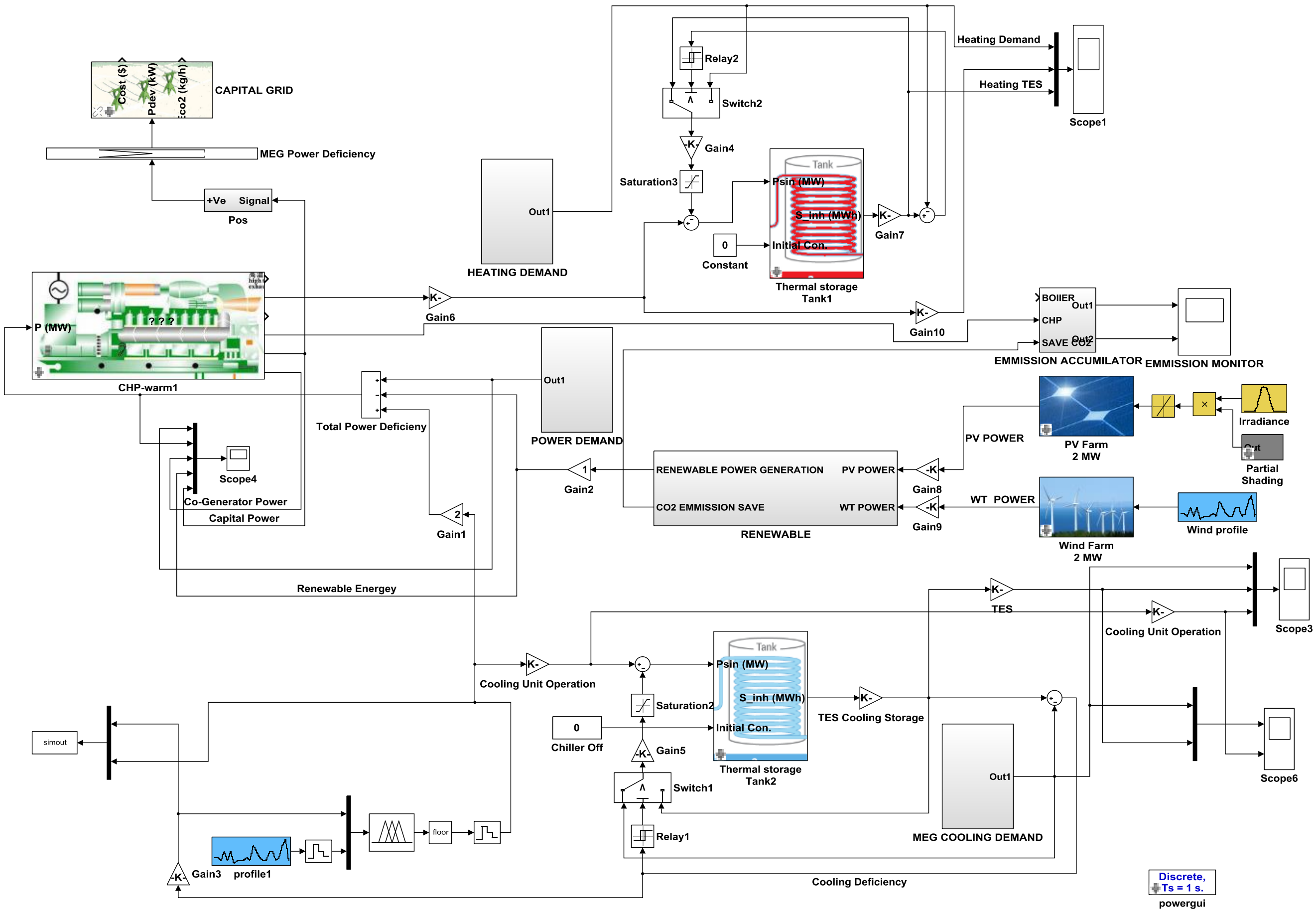


Fig. 12: Simulink Model for Proposed MEG system

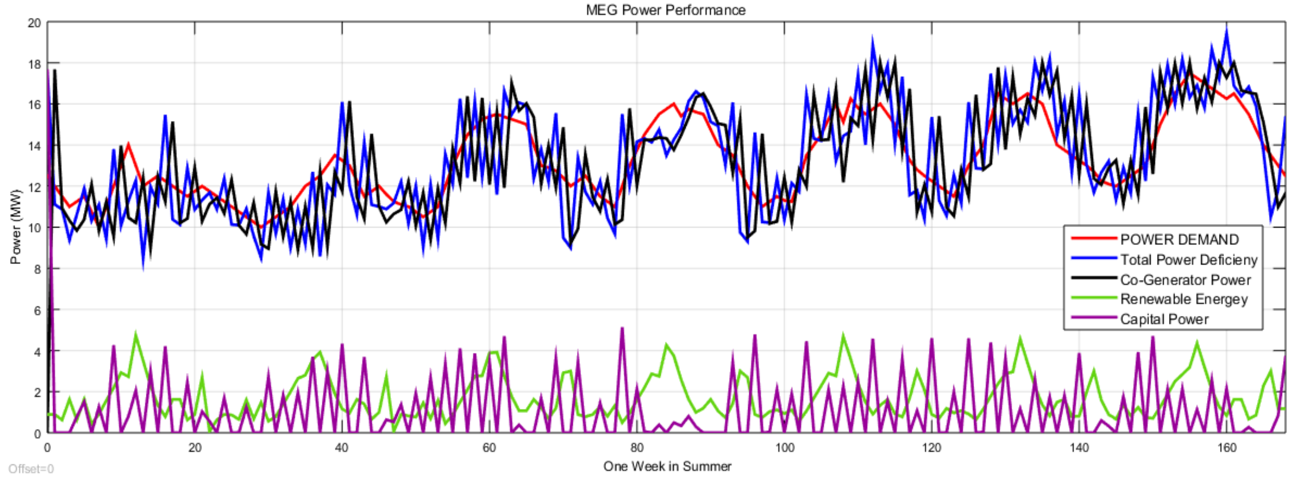


Fig. 13: Power profile for foundation MEG

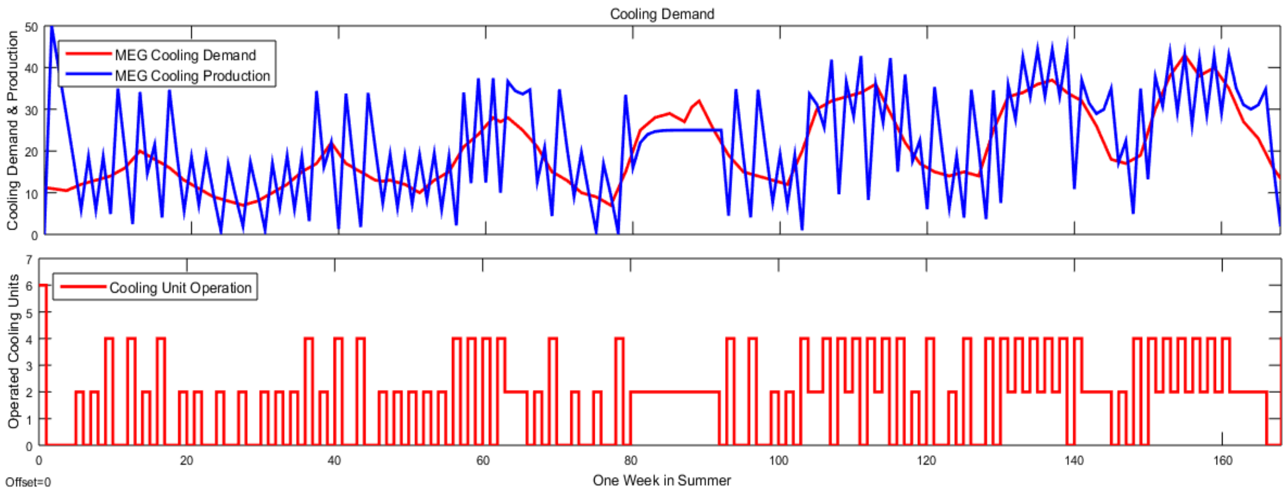


Fig. 14: Cooling profile for foundation MEG

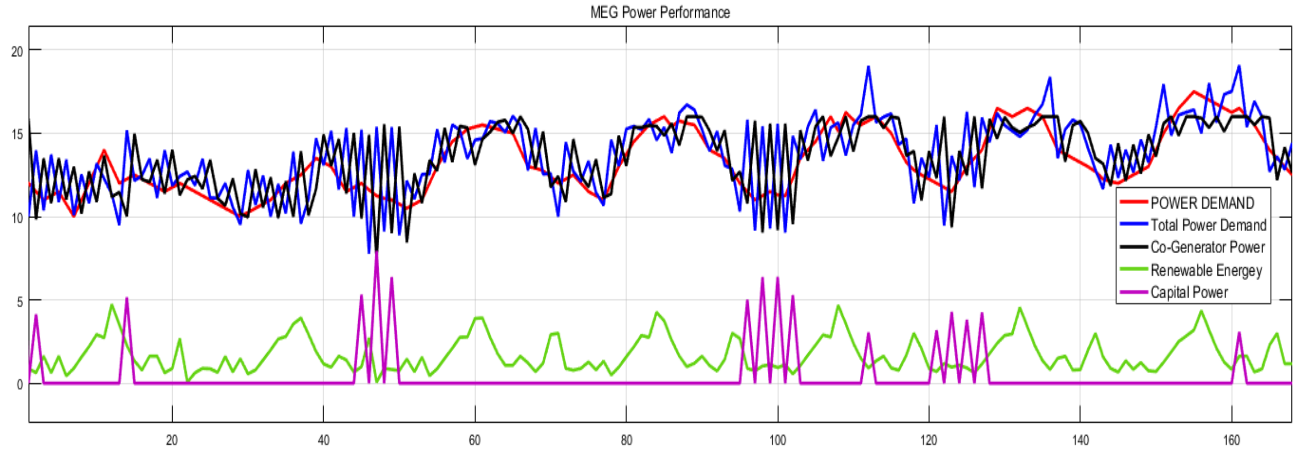


Fig. 15: MEG Power profile with utilizing co-generation and TES IPLs

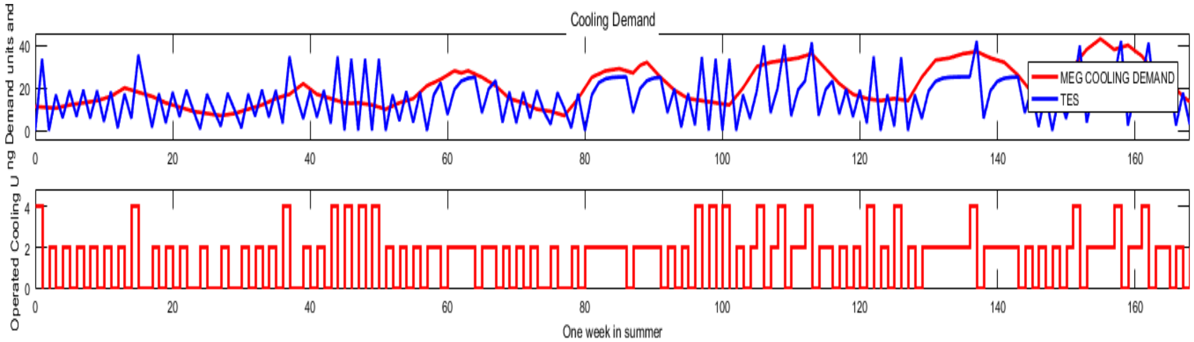


Fig.16: MEG Cooling profile with utilizing co-generaation and TES IPLs

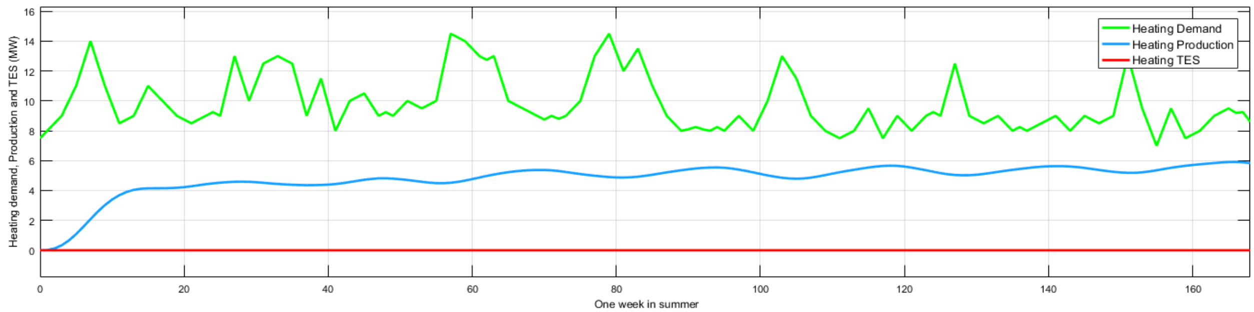


Fig.17: MEG Heating profile with utilizing co-generation and TES IPLs

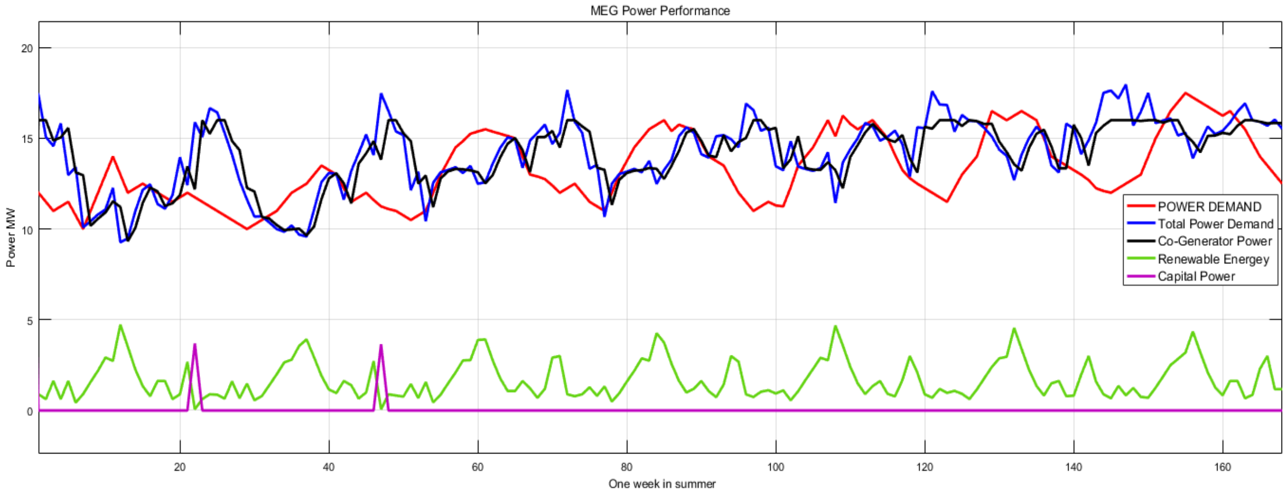


Fig. 18: Power profile for a resilient MEG comprises IPL-1, IPL-2 and IPL3

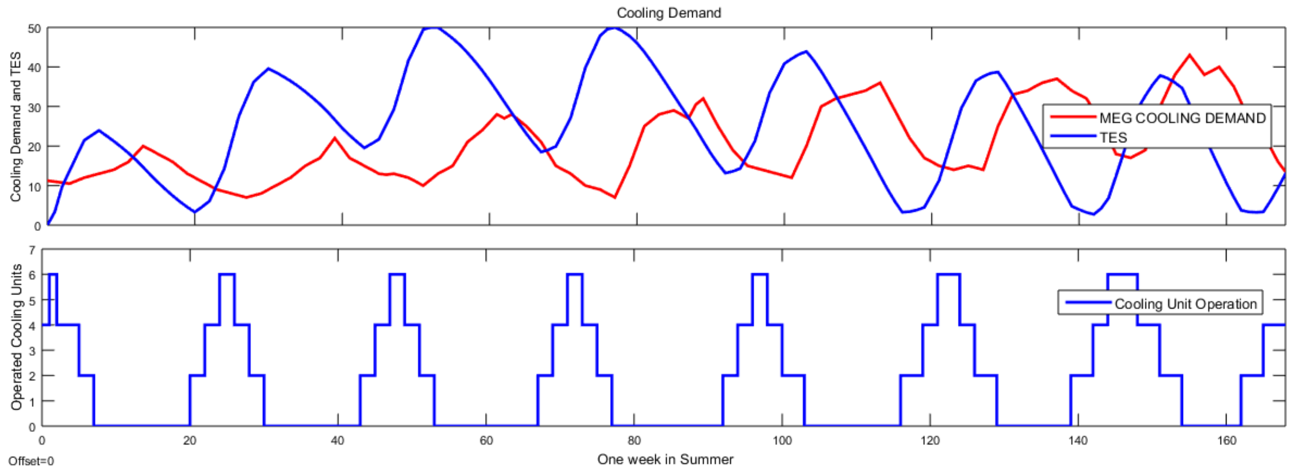
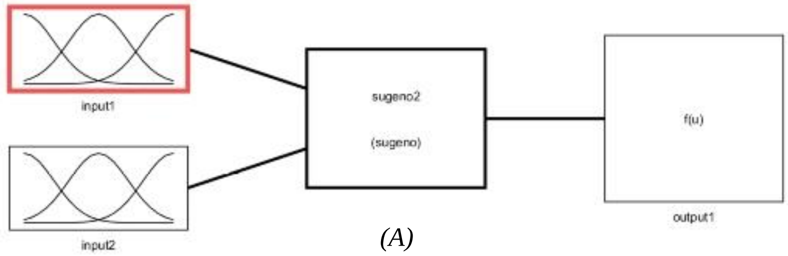
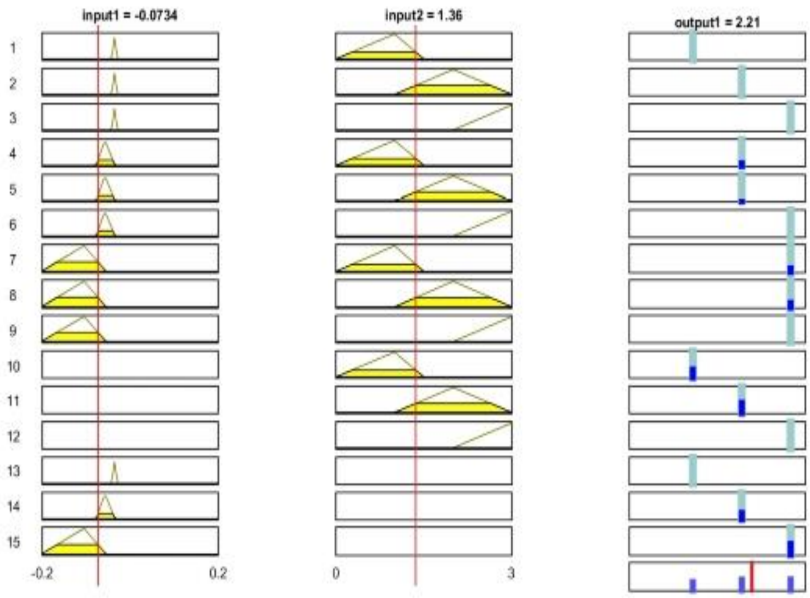


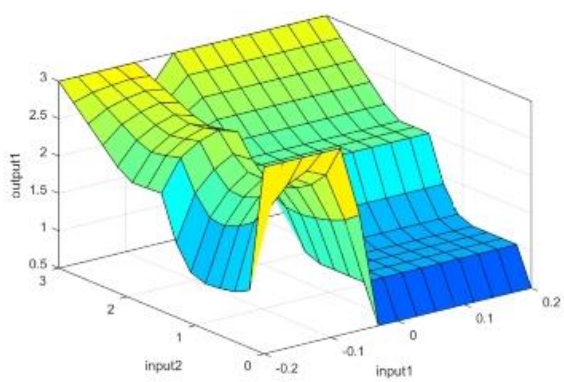
Fig. 19: Cooling profile for a resilient MEG comprises IPL-1, IPL-2 and IPL3



(A)



(B)



(C)

Fig. 20: Fuzzy control Members and surface

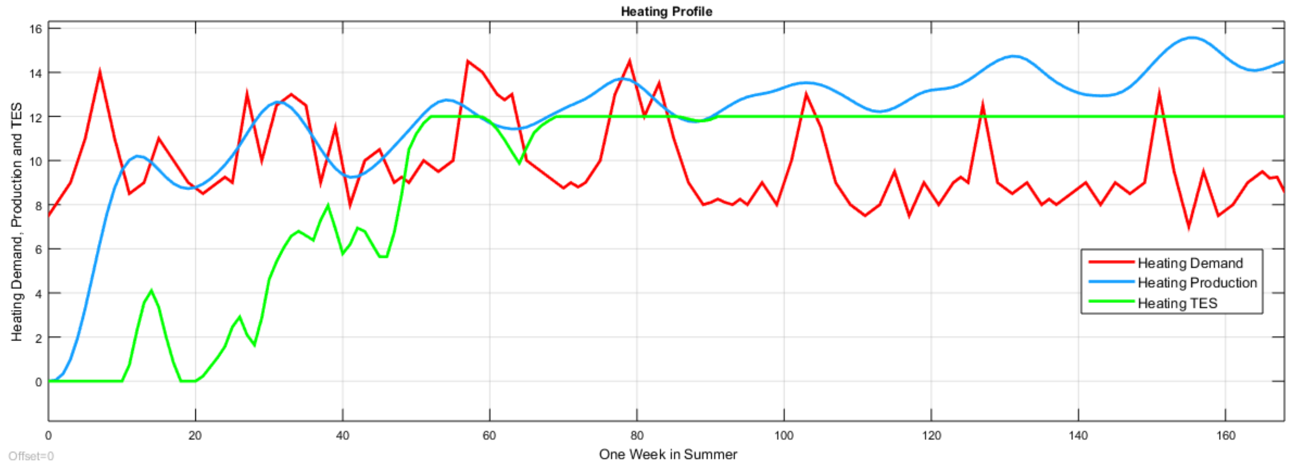


Fig. 21: Heating profile for a resilient MEG comprises IPL-1, IPL-2 and IPL3

Table 1: Chiller units coffeciant of operation (COP) and rated sizes [7]

Thermal Cooling	**Size (Tons)**	**Size (KWe)**	**COP**
	3500	2100	6.0

Table 2: Risks and Hazards at the MEG

No.#	Grid Type	Hazard Event	Severity	Frequency	Propability	Avoidance	Class	Hazard Level	Adverse Effects	Action (remidial or preventation)	Requirmed IPLs
		SCORE	*1 = Negligible 2 =Marginal 3 = Critical 4= Catastrophic*	*1 = Less 2 = yearly 3 =Monthly 4=Weekly 5=Daily*	*1 = Negligible 2 = Rarely 3 = Possible 4 = Likely 5 = Common*	*1 = Likely 3 = Possible 5 = Impossible*	*3-4= Very Low 5-7= Low 8-10= Moderate 11-13= High 14-15= Extremly High*	*1 = Low 2 = Moderate 3 = High*	On Human On Facility On Environmwnt		
1	Electrical MEG	Over load (above the grid Capability)	4	3	4	1	8	H	Demand not Serveed (DNS) Overheated transmission and distribution cables, Asset Damage, fire and power blackout Fire cause CO_2 Emmission	1- Upgrade grid capacity 2- Shift on-peak power demand 3- dynamic grid mapping based on load demand and priority	1- Cost Money and Time 2- Intelligent Energy Stotage System(super capacitor, Fly Wheel, TES and pumped hydro, or hydrogen storage 3- Intillegent Fault Tolerant Controller 4- ranking the loads as per its proioritization level
2		MEG has lack of DER	4	3	3	3	9	H	Interruption on service Power inturruption and/or blackout Lack of DER= more demand on Fossil fuel generators which cause Emmission	High dynamic performance from the distributed power and energy system by : • Store off-peak power	1- Intillegent Energy Stotage System (super capacitor, Fly Wheel, TES and pumped hydro, or hydrogen
3			3	5	5	3	13	H	Disturbance on service		

		Varity of on site renewable sources							Intermittency and non-coincidence of power production Lack of DER= more demand on Fossil fuel generators	production for using at on-peak demand • Utilize Gas Generator • Connect to Capital Grid (Utility)	storage. 2- Following Generator (fuel cells, micro-gas turbines, and hybrid fuel cell gas turbine systems) 3- Higher level Self-Healing Management Controller
4		Integration of multi sources DERs	2	5	5	3	13	H	Operation Failure of Sensitive Devices Negative impacts on grid parameters such as active power (P), reactive power (Q), voltage (V), phase shift (α) and frequency (f). On other word Bad Power Quality Excessive on Energy Resources and Emission	1- full utilization of DERs to increase energy efficiency 2- improve power quality 3- enhance system stability	1- Advanced D-FACTS system on AC/DC MEG to achieve resilient MEG 2- Create Robust KPI parameters able to optimize feedback control coefficients
5	Cooling MEG	High correlation of cooling demand with electricity demand	4	5	5	3	13	H	Demand not served Increase on-peak electricity demand could cause interruption and/or blackout Increase demand on Fossil Fuel generation	Shift on-peak cooling demand to off-peak demand	1- Utilize TES tanks 2- Predictive energy management
6		MEG contingency with lack of Chiller unit	4	3	3	3	9	H	Unconfortable condition for human Can't meet the on-peak cooling demand	1- Store off-peak cooling production for	1- Utilize TES tanks 2- Intilegent contingency

									Using individual A/C units lead to increase Global Wormming	using at on-peak demand	energy management (for immirgency procedure)
7	Heating MEG	Irregualr hot-water demand	3	5	4	3	12	H	Uncomfortable condition for human Failure to meet the Hot water on-peak demand Alternative heat sources like furnace produce emission	1- Store off-peak Hot water production for using at on-peak demand	1- Utilize TES tanks 2- Predictive energy management
8	Transportation	Transportation energy demand	4	5	5	1	11	H	Loss of Lifes , Injury and delay failure in energy threaten the safety for properities and the public Back-up Engines works using Fossil Fuel which increase Emission	1- Achieve energy management balance between transportation units and MEG for more reliability and security enhancement, reduced emissions and improved energy quality.	1- Energy Stotage System (super capacitor, Fly Wheel, TES and pumped hydro, or hydrogen storage. 2- Following Generator (fuel cells, micro-gas turbines, and hybrid fuel cell gas turbine systems) 3- Intillegent management Controller
9	All	Earth Quake	4	2	2	2	6	M	Loss of Lifes , Injury and delay failure in energy threaten the safety for properities and the public Spreading the damages and may initiat new hazards	Isolate the affected area from the service	Intillegent Management Controller
9	All	Water Flood	4	2	2	2	6	M	Loss of Lifes , Injury and delay	Isolate the affected area	

									failure in energy threaten the safety for properities and the public	from the service	Intillegent Management Controller
									Spreading the damages and may initiat new hazards		

Table 3: SIS operating condition

SIS Operating Condition	Process	Protection Available	Failure Indication
Normal	Operating Normally	Yes	N/A
Fail-Safe	Falsely Operating	N/A	Yes
Fail-Danger	Operating Normally	No	Without Diagnosis

Table 4: failure rate and repair time [14]

Type	Failure Rate (f/yr)	Reliability $e^{-\lambda T}$	Probability of Failure $1 - e^{-\lambda T}$	Repair Time (h)
PV	**0.11**	**0.8958**	**0.1042**	**72**
WT	**0.21**	**0.8106**	**0.1894**	**60**
Co-generator	**0.18**	**0.8353**	**0.1647**	**12**
Capital grid	**0.000184**	**0.9998**	**0.000184**	
Chiller		**0.95** [15]	**0.05**	
FC	**0.11**	**0.8958**	**0.1042**	**72**
Battery	**0.22**	**0.8025**	**0.1975**	**60**
HRSG	**0.16**	**0.8521**	**0.1479**	**16**

Table 5: typical outage rate for a consumer [16]

Contributor	Minutes/year	%
Generation/transmission	0.5	0.5
132 KV	2.3	2.4
66 KV and 33 KV	8	8.3
11KV and 6.6KV	58.8	60.7
Low voltage	11.5	11.9
Scheduled shutdown	15.7	16.2
Total	96.8	100