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DESIGN & IMPLEMENTATION OF SMART GRID USING CELLULAR NETWORKS AS ITS AMI BACKBONE

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Abstract
To solve the limitations of current power grid, Smart Grid is the solution. Its backbone is AMI (Advanced Metering Infrastructure), but its major problem is lack of unified data transmission infrastructure within the grids which should able to send big amount of data collected from each smart meter of a town or city to the center in cheap and secure way. In the current design of AMI in SG needs the implementation of a separate/mix transmission data infrastructure which will have very high cost. So, we introduce the use of Cellular networks in transmitting consumer data (usage and controlling) to the center and vice versa. We have designed a system where smart meters equipped with Cellular SIM Cards and Wi-Fi technologies communicate directly with the Hub in a secure way, bypassing the need for extensive infrastructure. The Wi-Fi in smart meters will be used in IoT of customer's home equipment management. This system could be deployed in the whole country just by installing smart meters and renting Cellular Companies Transmission infrastructure to send each customer data to the Hub. This design has been simulated in MATLAB. So, this approach associated with low-cost, high security and easy maintenance as the Cellular network's companies will be responsible for its maintenance just like their new cellular sites. This re-search provides a blueprint for utility companies and policymakers to upgrade electricity systems economically and efficiently using/renting already installed Cellular infrastructure.

INTRODUCTION

Traditional methods of measuring and controlling usage of electricity have their issues, and we need something more advanced. So, Smart Grid is the solution. Its back-bone is Advanced Metering Infrastructure (AMI). It is like the backbone and brain behind Smart Grids. This re-search looks at a way to make our electricity systems smarter without costing too much. The usual ways of using, controlling and measuring electricity have some problems,
So, we're trying to find a better and cheaper solution [1]. As the major problem in current AMI is sending

back the big amount of data collected from each smart meter of a town or city to the center in cheap and secure way. Right now, if we want to set up a separate way to send data, it's really expensive. The current designed for this task need a separate infrastructure or a mixe of diffrent technologies which will be very costly if implemented in certain area or whole country. So, we came up with a solution: let's use the technology we already have, like Cellular SIM Cards and Wi-Fi, to send data from people's meters to the main hub. A key advantage is the elimination of additional infrastructure requirements, just the smart meters with these technologies inside. Our main goal is to create a system where smart meters, with Cellular SIM Cards and Wi-Fi, can talk directly to the main hub without needing a bunch of extra equipment. This way, we can set up a system that works well without costing too much. Our research aims to show that using AMI in a Smart Grid can be done in a practical and cost-effective way. The special thing about our idea is that it's not just a simple solution; it also saves money. By showing how practical and good this way is, our research helps the development of Smart Grids. It gives a guide for companies and people in charge to make electricity systems better with-out spending too much money. So, in a nutshell, our work is about making Smart Grid technology cheaper and more doable for lots of people. And it will pave the road for the implementation of Smart grid country wise.

The previous work on this topic is a mixed system where data from the smart meter are sended via fiber optic or Wi-Fi or PLC or DSL or Satellite [2-3]. The novelty of our work is to use only Cellular network for AMI structure throughout the smart grid.

Current Proposed Model of AMI in Smart Grid

The current model of smart grid and AMI is shown in Fig. 1. It is a complex model and uses various technologies in its ami infrastructure. It uses many technologies like fiber optic wimax, DSL, satellite etc. at the same time. Incorporating such technologies will be costly and more complex [4].

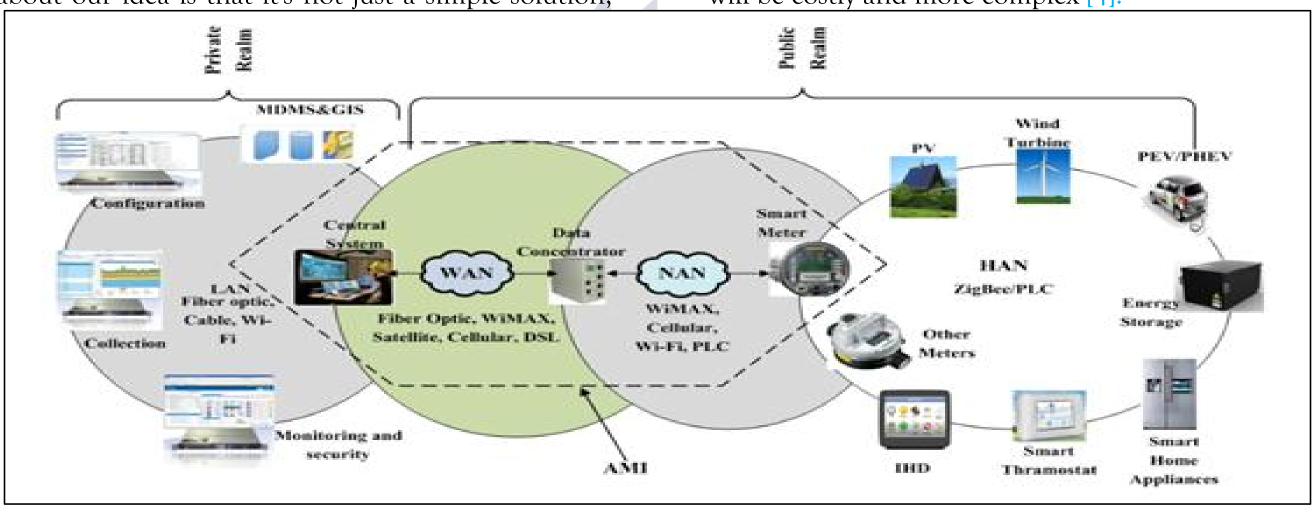

Figure 1. AMI Current Architecture.

1.2 Current Arechitecture of Cellular network

The current cellular network is being evolved with the passage of time. The 2G cellular network as shown in Fig. 2 is based on the circuit switching and therefore can only support the voice call over the 2G network. The transfer of data over the cellular network was enabled by the Packet Radio Services known as GPRS which was and upgrade for the cellular networks from 2G to 2.5G which enabled the users to send the data via packet switching networks for up to 40Kbps speed. The carrier frequencies used in the 2G cellular network are 900 MHz and 1800 MHz [5].

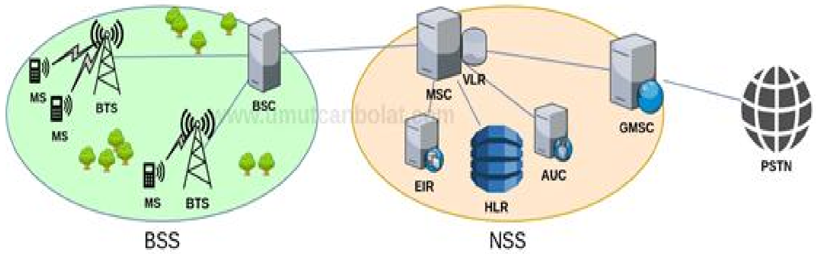

Figure 2. 2G *Cellular Network infrastructure.*

The current architecture of 3G and 4G networks are shown in Fig. 3. The data from smart meter will go through these networks in order to reach to the center. In 3G network we will have both circuit switch network and packet switched networks. The data will go through packet core network. In 4G network we have only packet core network, so data from smart meter will be transmitted through packet core network.

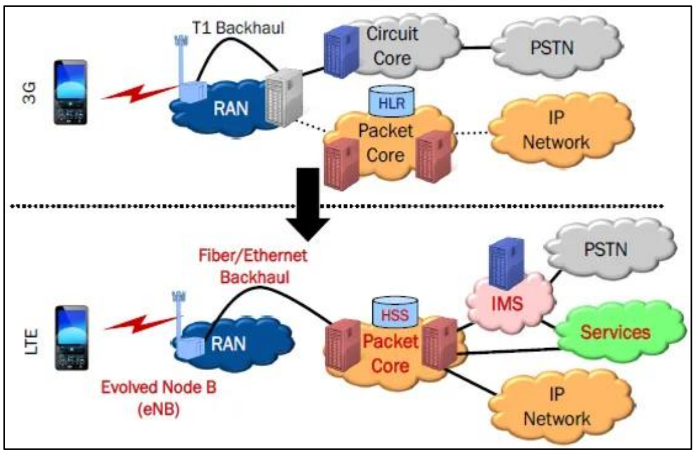

Figure 3. Current GSM Network Architecture (3G/4G)

The bandwidth used in 3G network is 25MHz while that of 4G is 100MHz. Both of them are suitable for Smart grid data transfer. Because we need 2Mbps data for each customer to send it from his/her house to the utility center. The carrier frequencies used in the 3G cellular network are 850 MHz and 2100 MHz. While The carrier frequencies used in the 4G cellular network are 1800 MHz and 2100 MHz

Table 2.1 Comparison of Frequency Bands for Cellular Technology Generations

Generation	Technology	Frequency Band	Details
2G	GSM	900/1800 MHz	Basic Voice, SMS and Low Speed Internet
3G	UMTS	850/2100 MHz	Faster Internet Speeds with MMS
4G	LTE	1800/2100 MHz	High Speed Internet for Broadband

CURRENT GAP IN IMPLEMENTATION OF SMART GRID

Smart grid is not fully implemented anywhere in the world (some developed countries have partially implemented it). And the main issue is lack of infrastructure of Transmission of AMI data from consumer to Utility and vice ver-sa. Implemented new infrastructure will be costly and will be more vulnerable to security concerns. So, the main problem is "the lack of data Transmission infrastructure which should be able to send/receive big amount of data collected from AMI (mainly) of concern area to the Hub site in cheap and secure way" [6].

Simulation of Smart Grid using AMI as its BB

Simulation of the smart grid using AMI as its backbone has been used to show the proposed solution.

3.1 Simplicity of new Proposed Model

The new model is very simple and straight forward. The data from smart grid generation & transmission module is fed to AMI (Advance Metering Infrastructure) system. The parameters are then measured by Smart meter and send it to its Hub site through its GSM module installed in it via Cellular network. The data from the Cellular network Hub is then sent to control center of Utility Company for control and billing etc. Cellular Network (2G/3G/4G) is responsible for data transmission controlled by third party. So, no maintenance of that part will be upon utility companies.

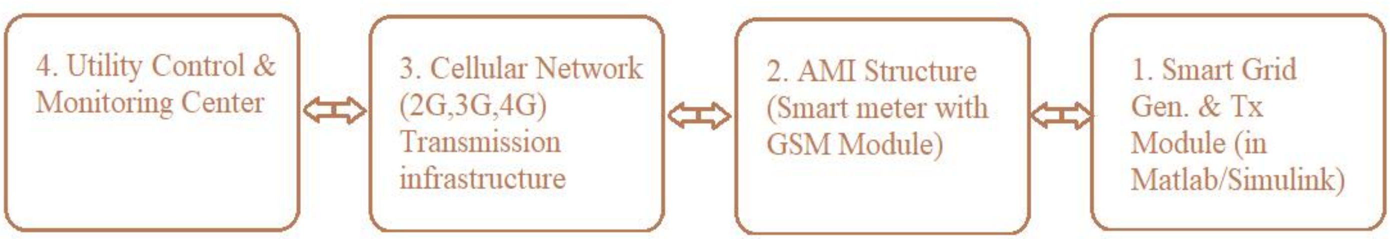

Figure 4. Block diagram of proposed System

The data coming from AMI is then fed into Monitoring and Control center from Cellular network Hub site where the data of the smart grid can be monitored and controlled 24/7.

3.2 Smart Grid

An advanced electrical grid system that uses digital technology to improve the efficiency, reliability and sustainabil-ity of electricity distribution and consumption is called a smart grid. It is different from the traditional power grids that are linear and centralized in nature; instead, it is characterized by flexibility and interactivity due to integration of various technologies and approaches. As shown in Fig. 4, the first block is the smart grid part and its

Genera-tion and Transmission section will be shown in the Matlab/Simulink simulation.

3.3 Smart Meter with SIM Card in AMI

The main part of AMI is smart meter. It is an electronic device for measuring usage of utility power/energy and transmitting it over SIM (Subscriber Identity Module) card through cellular networks is what we call a smart meter with a SIM card system on board [7-9]. The SIM card allows the smart meter to access different mobile net-work types (2G, 3G, 4G) where it will send data to its Hub from where it is forwarded to utility company center via an already established linked. It basically needs 350 kbps to 2 Mbps bandwidth to transmit data to the hub [10-11]. The smart meter would be smart enough to detect any fault in the system and send the information to the control center.

Figure 5. Smart Meter with SIM Card

3.4 Cellular network Data Transmission Infrastructure

The data from the GSM module of smart meter will be than send through already existing data transmission infrastructure
of Cellular network. This data is than received at the Hub center of cellular network. From here the data will be transmitted to Utility control center via already established links preferably fiber optic link.

3.5 Monitoring & Control center

Smart grids contain a very important facility known as the monitoring and control center. This facility is in charge of managing, supervising and optimizing the grid's operations. The center uses advanced technologies and data to make sure that the grid operates efficiently, reliably and safely. The data from control center will be used to bill the customers [12].

4.1 MATLAB/SIMULINK for Proposed System

This section discusses the MATLAB/Simulink model for the system. The Fig. 6 shows the complete modeling of the smart grid and the communication system along with the AMI.

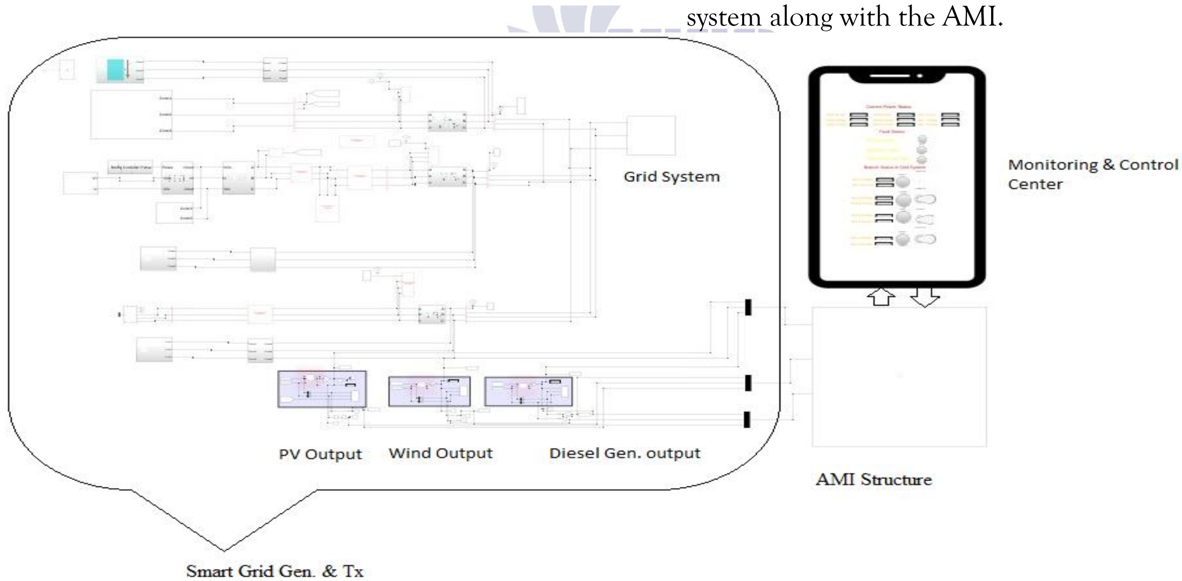

Figure 6. Complete block diagram of Proposed system using Matlab/Simulink

The smart grid consists of power generation plants including diesel generator, PV System and Wind which are con-nected to the utility via busbars, transmission lines, step up and step-down transformers, capacitor banks for reac-tive power compensation. Various faults are also generated using the fault modules for simulation of faults in all the three power generation systems. The system is divided into various blocks the Diesel generator setup is organized on the top of the Simulink model with a three-phase output connected to a three-phase busbar for the diesel genera-tor along with protective devices and fault simulating block. The backup of the generator is also implemented as a block in case there is disconnected of the diesel generator due to short circuit fault in the lines.

The PV generation block is setup at the center of the Simulink model here the PV generation is in DC which is fed to the boost converter MPPT (Maximum Power Point Tracking) and signal generator for boost converter. The DC is fed to the inverter block which converts this DC power to the three phase AC power. A backup for the PV setup is also implemented in the block in case of any disconnection.

The transmission line model is implemented which is three phases along with compensation filters, overcurrent relay and fault simulation block. The last one is the wind generation system which generates three phase AC also has the overcurrent protection, fault simulation block & backup block. It has three main modules, first one is the Smart Grid Module, second one is AMI structure Module and third one is Utility Monitoring and Control center. There are also measurement sections for each of the generation sections comprising of set of scopes, labels, goto blocks and to workspace blocks.

4.2 Diesel Generator Section

The close up view of the diesel generator is shown in the Fig. 7, the three phase busbars are connected to the diesel generator bus which measures the three-phase voltage and current of the system. A fault simulation module is also connected to the busbars to test the system under various fault conditions. The busbar is further connected to Relay G which will isolate the system in case of any fault. The busbars are further connected to the utility. A PV backup of 2.2MW is also connected with the Generator Bus to provide the required surge and load following for the load [13].

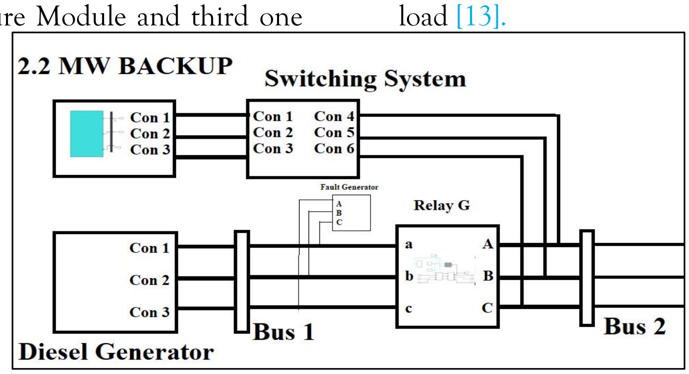

Figure 7. Diesel Generator System

4.3 PV Generator Section

The PV generation system can be seen in the Fig. 8 the PV system has the models of the PV panels enclosed with-in the subsystem. The output of the modules is fed into the boost converter which boosts the voltage from the PV system in accordance with the pulses from the MPPT controller which are the Boost Controller Pulses. The output of the boost

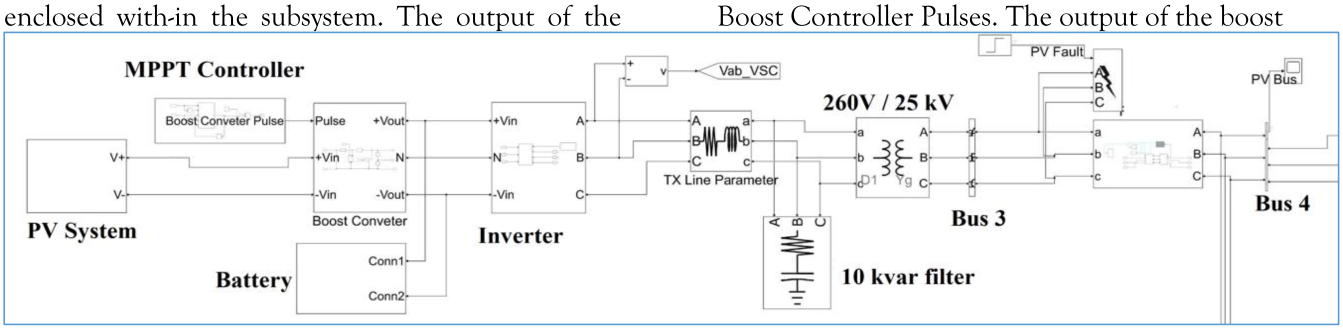

Figure 8. PV Generator Section.

Converter is further fed into the inverter and the battery is connected in parallel with the inverter input and boost converter which can also be considered as the DC link in this case. The inverter generates a three-phase out-put further connected to the transmission line with the resistive and inductive effects throughout the line [14]. The 10 Kvar Filter is connected in parallel at the receiving end of the transmission line to compensate the losses and reactive power due to inductive nature of the transmission line. The three-phase power is then fed

into the three-phase transformer with a rating of 280V/25KV further connected to the relay PV.
Here the three-phase fault module named and PV Fault is connected to the all three phases to simulate a fault condition with the lines and the relay PV to disconnect the line in case of any fault.
A PV backup of 100KW is also connected with the PV Bus 1 to provide the required surge and load following for the load [15].

4.4 Wind Generation System

The wind generation setup can be seen in Fig. 9 here the wind turbine generates a 3-phase electrical power which is at around 575V and is AC. The electric power from the wind turbine is fed into the step-up transformer which then converts the low to high voltage of 25 KV which is then connected to wind bus 1 via Relay W this relay will isolate the wind power generation system from the power network in case of any fault. The three-phase fault is simulated using a wind fault subsystem connected in parallel with the three phases of the wind power.

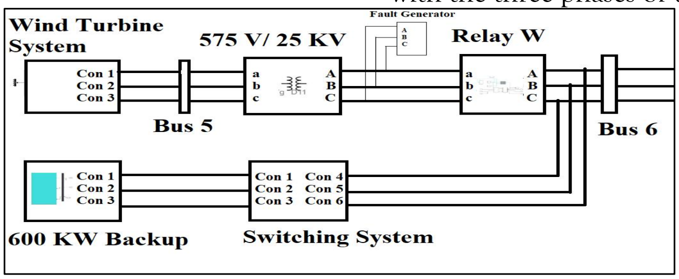

Figure 9. Wind Generation System

A PV backup of 600KW is also connected with the Wind Bus to provide the required surge and load following for the load [16].

4.5 The Grid

It is a ready-made module in Simulink/MATLAB. The busbars from all the generation systems are fed to the grid. It comprises of various three phase busbars connected to three phase measurement blocks. These are further con-nected to the three phase breakers and then to the respective loads. These mostly include the RL load blocks exhib-iting the characteristics of the lump loads.

5.0 Output Results

The result of each power generation section is given as follows.

5.1 PV Generation Output Results

The results of the model during the normal operating conditions are discussed in this section. Fig. 10 shows the arrangement of the PV output which is measurement block of the PV generation this has various incoming tags from the bus bars Vabc_PV, Iabc_PV which then contributes to plot the active and reactive power of the system. K is gain for conversion of values to KW. Oscilloscopes are labelled as P_B1 and Grid as it will show active power, voltage and current waveforms. The three-phase voltage and current takes are then fed to the selector blocks to select the output of the phase required to plot on the scope. The Vab_VSC tag is also connected to the scope for the plot [17].

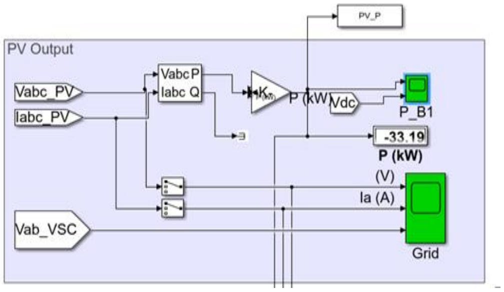

Figure 10. PV Power Output Module

The PV output voltage, current and power graphs from osciliscopes labled as Grid and P_B1 has been shown in the following Fig. 11.

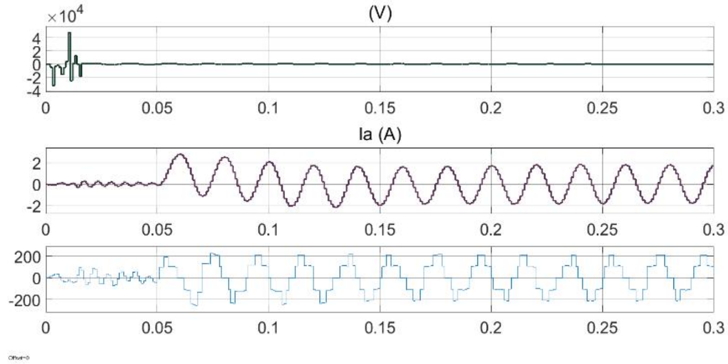

Figure 11. PV Generated Power, Current & Voltage Graphs

5.2 Wind Generation Output Results

The wind plant output measurement block can be seen in Fig. 12 the inputs are the three-phase voltage and current of the wind bus. The Vabc_Wind is for the voltage and the Iabc_Wind is for the current. Both of these are fed to the block which estimated the active and reactive power of the busbar fed to the scope to observe the power output. K is gain for conversion of values to KW. Scopes are labelled as P(kW)1 and Grid1 as it will show active power, voltage and current waveforms. The three-phase voltage and current are then fed to the selector switches which determine the phase that needs to be displayed on scope for further observations of the waveforms [18].

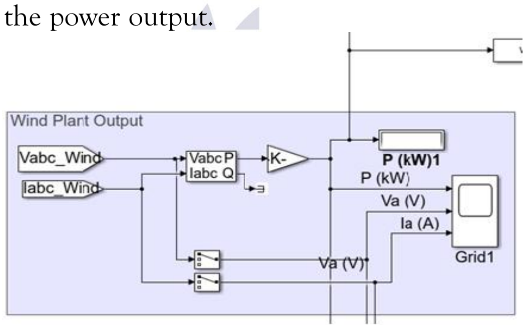

Figure 12. Wind Power Output Module

The Wind output voltage, current and power graphs from oscilocopes labled as P(kW)1 and Grid1 has been shown in the following Fig. 13.

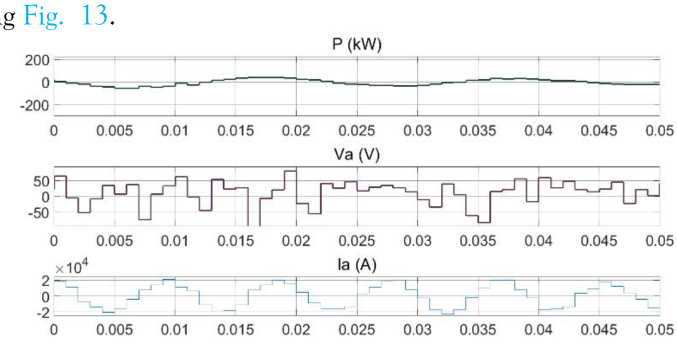

Figure 13. Wind Generated Power, Current & Voltage Graphs

5.3 Diesel Generation Output Results

Fig. 14 shows the diesel generator output measurement block here the three-phase voltage and current are input which are Vabc_DG for voltage and Iabc_DG for current of the three phases. These signals are input to the power measurement block with then calculate the active power P and reactive power Q for the system. K is gain for con-version of values to KW. Scope is labelled as Grid2 as it will show voltage and current waveforms. The power is then fed to the scope and display [19]. The Vabc_DG and Iabc_DG are fed to the selector blocks to select the voltage and current to be displayed on the scope.

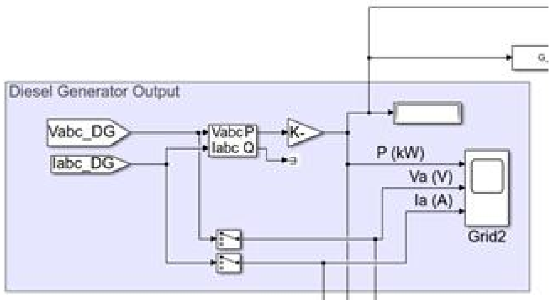

Figure 14. Diesel Generator Power Output Module

The Diesel Generator output voltage, current and power graphs form oscilloscope labled as Grid2 has been shown in the following figure.

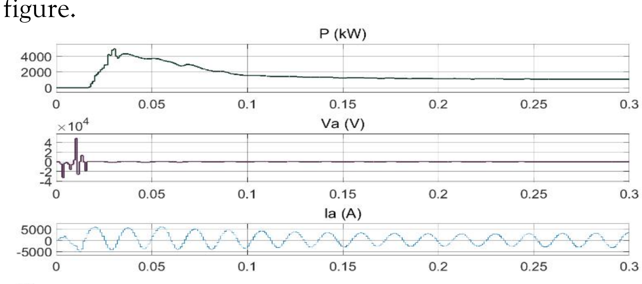

Figure 15. Diesel Generated Power, Current & Voltage Graphs

6.1 AMI Structure

As shown in Fig. 19 the message 1 contains the measurements of the power in KW of the PV, Wind and Diesel, the message 2 has the measurements of the current from PV, Wind and Diesel power generation blocks whereas the message 3 has the measurements of voltage of the PV wind and diesel generation blocks. The message 4 has the measurements of the voltage and current of bus 1, 2, 3 and 4. The smart meter has GSM module in it which transmit customer data to its Hub site where it has been received and then forwarded to Utlity center via already established link. The clock signals are generated using the sine and clock block with two constant blocks of value 1 in both of them. Spectrum Analysir is also attached to check the power density spectrum if required [20].

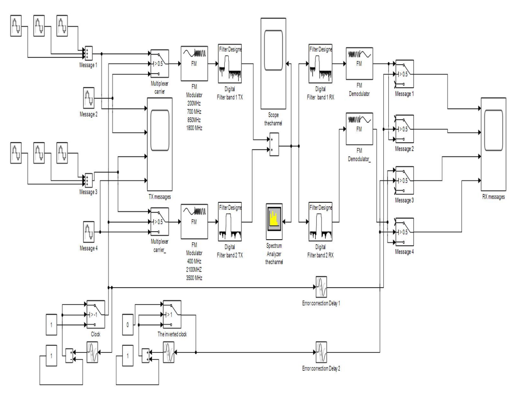

Figure 19. Block Diagram of Smart meter with GSM module using Cellular network

It has the following steps at ***Transmission end*** and the Tx messages on osciloscipe are shown in Fig. 20:

6.1.1 Multiplexing

The signal received from smart grid are passed through multiplexer. So it will convert all four signals into one.

6.1.2 Modulation

The signals are than modulated using carrier signals having frequencies of 900MHz and 1800MHz in 2G while 850MHz and 2100MHz in 3G network. And in 4G the carrier frequencies are 1800MHz and 2100Mz . The modulated signals of 900MHz, 1800MHz and 2100MHz are shown in the following figures of Fig. 16, Fig. 17 and Fig. 18.

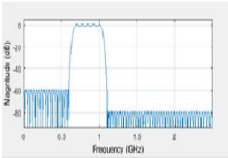

Fig. 16 Modulated siganal with carrier frequency of 900 MHz

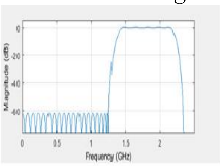

Fig. 17 Modulated siganal with carrier frequency of 1800 MHz

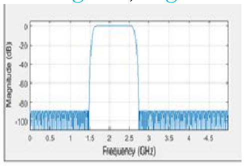

Fig. 18 Modulated siganal with carrier frequency of 2100 MHz

6.1.3 Filtration

The signals are than passed through band pass digital filter in order to allow only concern band to be transmitted.

The signal is then sent through air interface and passes through the Transmission backbone of the Cellullar Network (2G, 3G, 4G) and upon receiving at the hub site of cellular network the above procedure took place in reverse order.

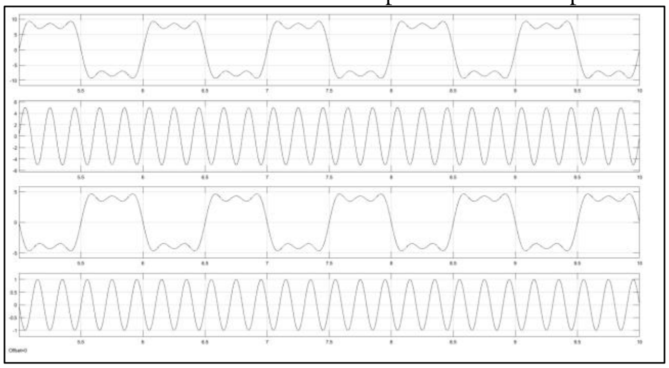

Figure 20. GSM module's Tx Messages

At ***Receiving end***, it follows the following steps and the signals received are shown in oscilloscope in Fig. 21:

6.1.4 Filtration

The signal received is passed through band pass filter first to receive the concern band and then fed to Demodulator.

6.1.5 Demodulation

The signal received are than demodulated, where carrier signals are separated from the base signals. And then it is fed to demultiplexer.

6.1.6 Demultiplexing

The signal received is then demultiplexed and here the Message 1, 2, 3 and 4 blocks are also fed with the error correction blocks. All the four different messages are then displayed on the scope.

Original 4 message signals are retrieved in the Hub site of Cellullar network. Here the signals ends its journey through Cellular network and then forwarded to Control room of Utility company via already established link preferably fiber optic link. [21]

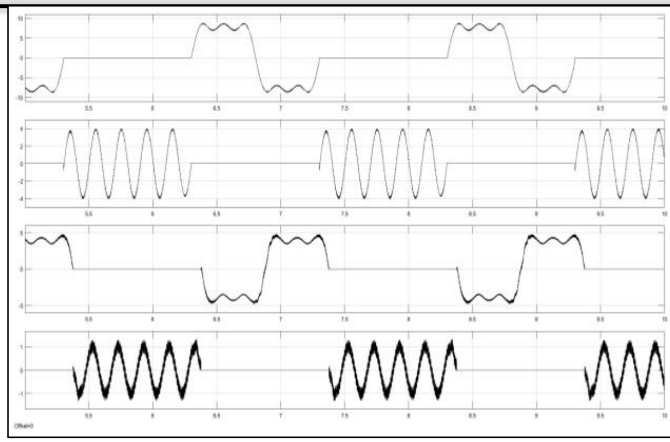

Figure 21. GSM module's Rx Messages

6.1.7 Collecting Data from Multiple Smart Meters

The data from each smart meter is send to the Hub site (MSC) via already existing data transmission infrastructure of Cellular network, where it will be combined and then forwarded to Control room of Utility company via an already established link preferably fiber optic link.

7.1 Monitoring and Control Center

The signals received from GSM module is than passed to Monitoring and Control center where all the parameters are actively checked as shown in Fig. 22. The power/energy used by each customer can be easily checked after regular interval of times. And each customer is given unique number just like mobile phone number so billing became easy without need of any meter reader which will decrease the overall cost of the system [22].

It can further monitor all types of power parameters used in the smart grid. And it will show any fault at any particular part of the smart grid.

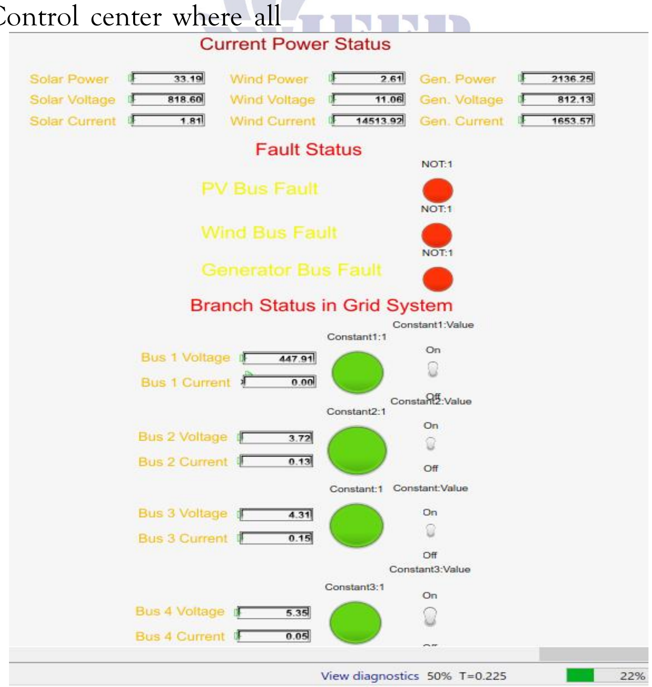

Figure 22. Parameters monitored & controlled in the Control Center

7.1.2 Security Advantage of Cellular network

Current cellular networks use advanced firewalls like NGFW, SIP and GTP which make it more protected. So, using this (Cellular network) in AMI infrastructure will make the smart grid more secure.

7.1.3 Bandwith Limitation & Nation wide Implementation

Each smart meter will send data only in text form so it uses less bandwidth of 200 kHz (400 kbps) each [23]. So, by implementing it nationwide it will use few GB/TB of data. For 1 million customers it will used almost 382 GB data. And the current advanced 3G/4G cellular network can conveniently handle it.

7.1.4 Power Consumption of new Smart meters

The extra power consumption of smart meter with SIM card will be very low and will require 2 to 4 watts of power like a smart phone device [24]. So, by implementing it in certain area will require few kilowatts extra power than old meters. And nationwide implementation will consume few Mega Watts extra power which would be manageable by utility companies with ease.

7.1.5 Novelty Contribution

The existing network in most developing countries are old traditional manually control grids. So, upgrading it to Smart grid need the novelty of our proposed system which will help to smoothly implement its bank bone (AMI structure) of Smart grid. And in developed countries the smart grids are partially implemented with the mixed data sending infrastructure of fiber optic, Wi-Fi, DSL, Satellite & PLC and with some traditional old grids. Our proposed system will unify the whole data network of smart grid into one complete data network eliminating multiple technologies network.

8.1 Advantages of AMI with GSM module

- It will be more secure because it will not need any new system as Cellular Networks are already quite secure as it uses advance firewall system for its network security.
- Its Maintenance cost will be low because the technical issues in the network will upon the Cellular network vendors and not upon utility company.
- No meter reader will be needed as the data of the smart meter will be available to the utility companies 24/7. So, they can collect monthly data easily to bill the customers accordingly.
- Its implementation will be easy because the utility companies only have to replace old Analog/Digital meters with new Smart meters with GSM module in it. And there should be an agreement between utility company and Telecom vendors to supply with the SIM Cards.
- It will provide 24/7 NOC Facility to the Utility companies to monitor and control the entire Grid smoothly and effortlessly.

9.1 Challenges

- The main challenge of this proposed system is the replacing of all installed Analog/Digital meters with Smart Meters having GSM module.
- The second challenge is the need of third party vendor for SIM cards provision and Maintenance.

10. 1 Conclusion

This research paper focuses on the implementation of smart grid with AMI using cellular networks 2G, 3G and 4G as its backbone. The system is designed and tested using SIMULINK in MATLAB. The smart grid is composed of a utility with various busbars and power distribution scheme along with the renewables integration with the system. The renewables include the PV and Wind generation blocks along Diesel Generation as an Independent Power Plant for the smart grid. A backup is provided for each power generation module to provide necessary power to the sys-tem in case of any fault. The smart metering system is deployed with the GSM module as communication back-bone of the system (AMI structure). The smart meter shows the power, voltage and current for the PV, Wind and Diesel Generator blocks along with the voltage and current for the Buses 1, 2, 3 and 4 respectively. The system is initialized with the utility and renewables generating powers the results are observed showing the distorted wave-forms due to initial surges. The faults for PV, Wind and Diesel Generator are introduced into the system during the initial conditions with the cellular network communicating the detection of faults in all the three system. The 2G GSM network successfully detects and clears the fault within 0.4 sec, the 3G performs the required operation within 0.3 sec and the 4G clears the fault within 0.2 sec of the simulation time. It is observed that the PV and Wind have the same speeds whereas the Diesel Generator lags behind for the fault detection and clearance times.

11.1 Future Work

The future work for the technology may include introduction of various power sharing modules for the smart grid. With integration of energy storage systems, the complexity of the system is increased with communication with the Battery Management Systems and all its parameters including state of charge and charging schedules for the bat-teries. The integration of Electric Vehicles charging and discharging can also be included with power sharing schedules in peak and off-peak times. The management schedules can be created for the charging of EVs in the off-peak times and using these EVs to meet up the increasing power demand during the peak hours. Another aspect can be intro-duction of Demand Response Schemes for the Smart Grid this can be done on basis of the load on the feeder and also using the smart plugs with may obtain the data of each device and also control then using the central management and control center of the smart grid. All these additional features will require more computational and communication resources including data storage and bandwidth of the system which can an objective to be achieved in the future work.

Nomenclature	
SM	Smart Grid
AMI	Advance metering Infrastructure
2G	Second Generation
3G	Third Generation
EVs	Electrical Vehicles
SIM	Subscriber Identity Module
PV	Photovoltaic
4G	Fourth Generation

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