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Modelling and Simulation of Natural Gas Generator and EV Charging Station: A Step to Microgrid Technology

Nazmus Sakib[1], Jakir Hossain[2], Eklas Hossain[3], Ramazan Bayindir[4]

[1]Marquette University, Klingler College of Arts and Sciences, WI 53233, USA

[2]Khulna University of Engineering & Technology, Department of EEE, Khulna- 9203, Bangladesh

[3]Oregon Tech, Department of Electrical Engineering & Renewable Energy, OR-97601, USA

[4]Gazi University, Faculty of Technology, Department of Electrical & Electronics Engineering, 06500, Turkey

nazmus.sakib@marquette.edu; jakirhossain471@gmail.com; eklas.hossain@oit.edu; bayindir@gazi.edu.tr

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Abstract Besides the negative impact on both the environmental and geological aspect because of the fossil fuel combustion-based power generation, the fossil fuels have almost been depleted, and hence an alternative fuel source is required. To meet the demand of the next generation power system, renewable and clean energy resources, such as solar, wind, tide, geothermal, and natural gas, can be the fuel of choice. In this paper, the concentration is limited to the natural gas generators and electric vehicle charging station besides the delineation of the entire microgrid testbed. In particular, this letter is associated with the modeling of the natural gas generators and the simulations for the different aspects and cases of the regarding system. Besides that, the EV charging station is also delineated with the necessary modelling, simulation, and analysis. All the results are verified by the Matlab/Simulink simulations and with necessary explanation.

Keywords Renewable Energy, Clean Energy, Microgrid Systems, Natural Gas Generator, EV Charging Station.

1. Introduction

Since the beginning of the indutrialization, combustible fossil fuel has been considering as the prminent source of energy. After that, when the electrification came as the blessings of the modern science, to generate electricity in a large scale, combustible fuels has majorly been used since then. Though it has some benefits considering the fuel efficiency, it has a number of negative influences on the environment as well as the geological aspect. The more the combustion, the more the carbon emission, hence the combustible fuel based-power generation causes serious environmental problem [1-4]. Not only that, due to the over use of the combustible fossil fuels like oil and coal, the depletion of these types of fuel may lead to the serious geological imbalance. Considering the environmental issues, as well as in search of the dependable fuel source, the power system-in order to meet the higher demand- is now at the stage to shift the choice of fuel [5-7]. The renewable energy-based power generation is the blessings that can meet the chaallenges of the next generation power demand [8,9].

Renewable energy resources are environmental friendly, free of cost, easily available in the environment, and nondepletable [10, 14]. To implement the renewable energy based-electricity generation, microgrid system has been adopted around the world. Microgrid system integrates several types of renewable energy sources, such as solar systems (PV), wind turbines, fuel cells, to the household and industrial loads [11-13]. It is a locally arranged distributed generation-based system and it requires secure communication for safe and uninterrupted generation. In microgrid system, in the case of urgent demand, antural gas generators provide the additional support. Though not one of the renewable energy rsources, natural gas promotes the usage of the clean energy. However, due to the high cost of the natural gas, they are only operated in the emergency need. Besides the natural gas turbine, in recent shift from the conventional fuel choices to the renewable and clean energy resources, EV charging station is one the areas where the microgrid-based system can be implemented.

In this paper, the concentration will be limited to the natural gas generator, and EV charging station besides the overall delineation of the entire microgrid system. Before the implementation of any physical system, mathematical modelling and verification of the system resources are required. For the proposed system of microgrid testbed, the modelling of the system resources along with the necessay simulation results will be discussed in this paper.

The contribution of this paper is as follows. In section two, the entire microgrid model is presented. Later, in section three, the natural gas generator modeling is presented including the excitation systems, off-grid operation, grid-tied operation, combined heat and power generation. In section four, the modeling of the Combined Heat and Power generation (CHP) is delineated. In section five, the EV charging station modeling is presented including the electric vehicle charging station levels, DC bus capacitance calculations, EV battery, battery charger, three phase inverter, LCL filter. Finally, in section six, the simulation and analysis are delineated for certain parameters of the natural gas generaotors in the microgrid systems.

2. Microgrid Model

Microgrid, in a locally adopted setup, incorporates several distributed generation units including the renewable resources and essentially it is possible to operate the entire system autonomously. The sources of microgrid generation are wind energy, solar energy, fuel cells, natural gas, and other energy sources [15-17]. To run it autonomously and as per the requirements of any circumstances of demand, the multiple and isolated sources of microgrid makes it feasible. In figure 1, the microgrid testbed endeavoured by University of Wisconsin-Milwaukee is depicted. Here, the microgrid system is modelled with the renewable energy sources and some storage systems. In this illustration, a 12 kW wind turbine, 100 kW solar panel, two 45 kW natural gas generators, and 50 kW fuel cells are connected to a bus-bar in left side, which is known as source side. And on the right side of the bus-bar, several loads are connected such as the electric vehicle charging station, 200 kW passive load etc.

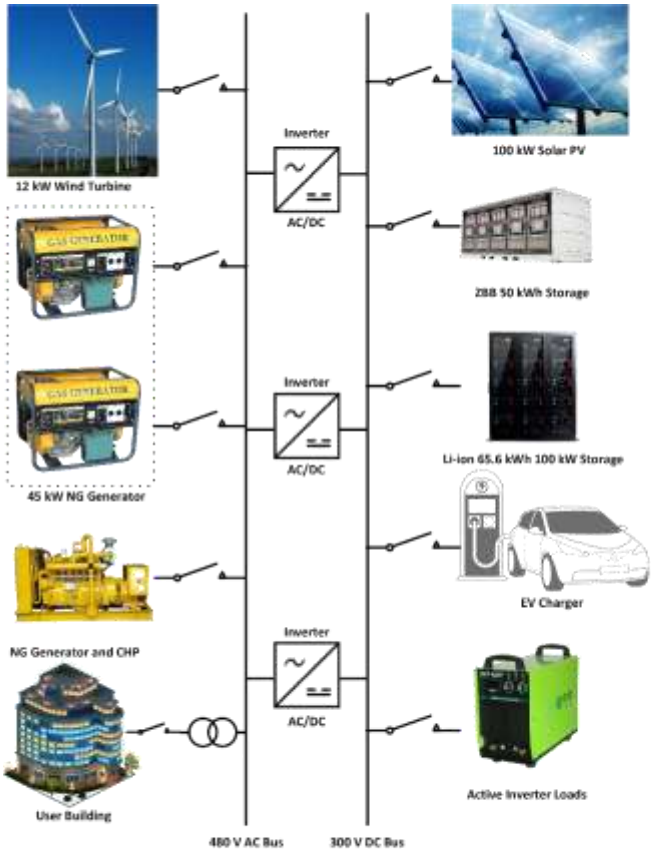

Fig.1: University of Wisconsin Milwaukee Microgrid Testbed.[5]

3. Natural Gas Generator

Natural gas generator can be defined as a wind turbine run by the natural gas as fuel. Here, electrical energy is generated from the ac synchronous generator. The most salient feature of the natural gas generator is it necessariliy has the fuel sustainability which is required to produce electrical energy with the constant voltage and frequency. Generally, when a load is applied to the microgrid system, the system voltage and frequency copnsequently experience a transient peak before settling, though not a consirable time required, at the steady state values [4]. Similarly, the transient occurs when the load is removed from the system. Here, the engine gevernor and generator exciter controls determine the duration and peak magnitude of the transient. But, to retain the system stability, the system must be able to maintain the voltage and frequency within the certain boundary limit either in the case of load changes or in the case of renewable enrgy generation changes [4]. The natural gas generator connected to a grid or microgrid (basic block diagram) is depicted in the figure 2. In this figure, the governor is dedicated to adjust the engine speed. Eventually, the engine speed is converted to the output frequency. The output voltage is regulated by the exciter. After that, in table 1, the salient attributes of the 1.5MVA machine used here is given. IEEE Standard 421.5 (the Institute of Electrical and Electronics Engineers) recommends three distinctive types of excitation systems such as AC type excitation systems, DC type excitation systems, and the static type excitation systems. Because of the fairly small size of the machines, in this letter, the Alternator Supplied Rectifier Exciter with Digital Control #2 exciter type is chosen [5, 12]. It is commonly known as ACIA. Block diagram of the exciter is illustrated at figure 3.

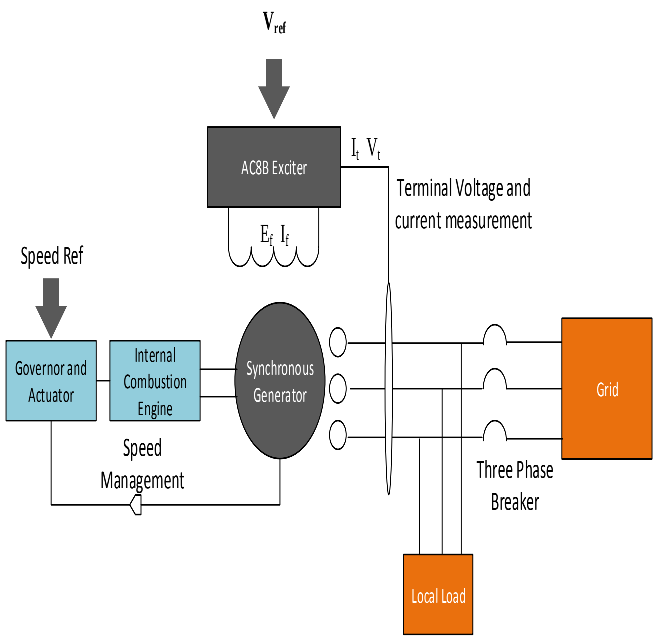

Fig. 2: The natural gas generator (basic block diagram) connected to a conventioan utility grid or a microgrid system.

Table 4. The Key parameters Natural Gas Generator	
Rated RMS Line to Neutral Voltage	6.9282 [kV]
Rated RMS Line Current	0.09 [kA]
Base Angular Frequency	376.991118 [rad/sec]
Armature Time Constant [Ta]	0.332 [pu]
Poitier Reactance [Xp]	0.011 [pu]
D:Unsaturated Reactance [Xd]	0.13 [pu]
D:Unsaturated Transient Reactance [Xd′]	0.03 [pu]
D:Unsaturated Transient Reactance Time (open)	[Td0′] 5.2 [s]
D:Unsaturated Sub Transient Reactance [Xd″]	0.022 [pu]
D:Unsaturated Sub Transient Reactance Time (open) [Td0″]	0.029 [s]
Q:Unsaturated Reactance [Xq]	0.51 [pu]
Q:Unsaturated Transient Reactance [Xq′]	0.228 [pu]

A. Excitation system

A Matlab/Simulink Model for the AC15 excitation system is presented in the figure 4. In this simulation, a step load of 0.85 power factor is applied at 20 sec and the load is removed at 40 sec, where the real power is 45 kW and the reactive power is 28 kVar. When the load is connected to the terminal voltage and the speed of the machine drop is as indicated in the figure. Also the terminal voltage and the speed of the machine increase, when the load is disconnected again.

B. Off-Grid Operation

The operation of a natural gas generator for the off-grid system is modeled and simulated using MATLAB/Simulink for a power rating of 49 kVA and givwn in figure 5. Simulation results of both the speed of the generator and output voltage along with the real and reactive power output are presented in the figure 6 and 7. While switching the load in 20th and 40th seconds, the transient peak voltage is almost 3 pu and it takes a long settling time to stabilize the system output.

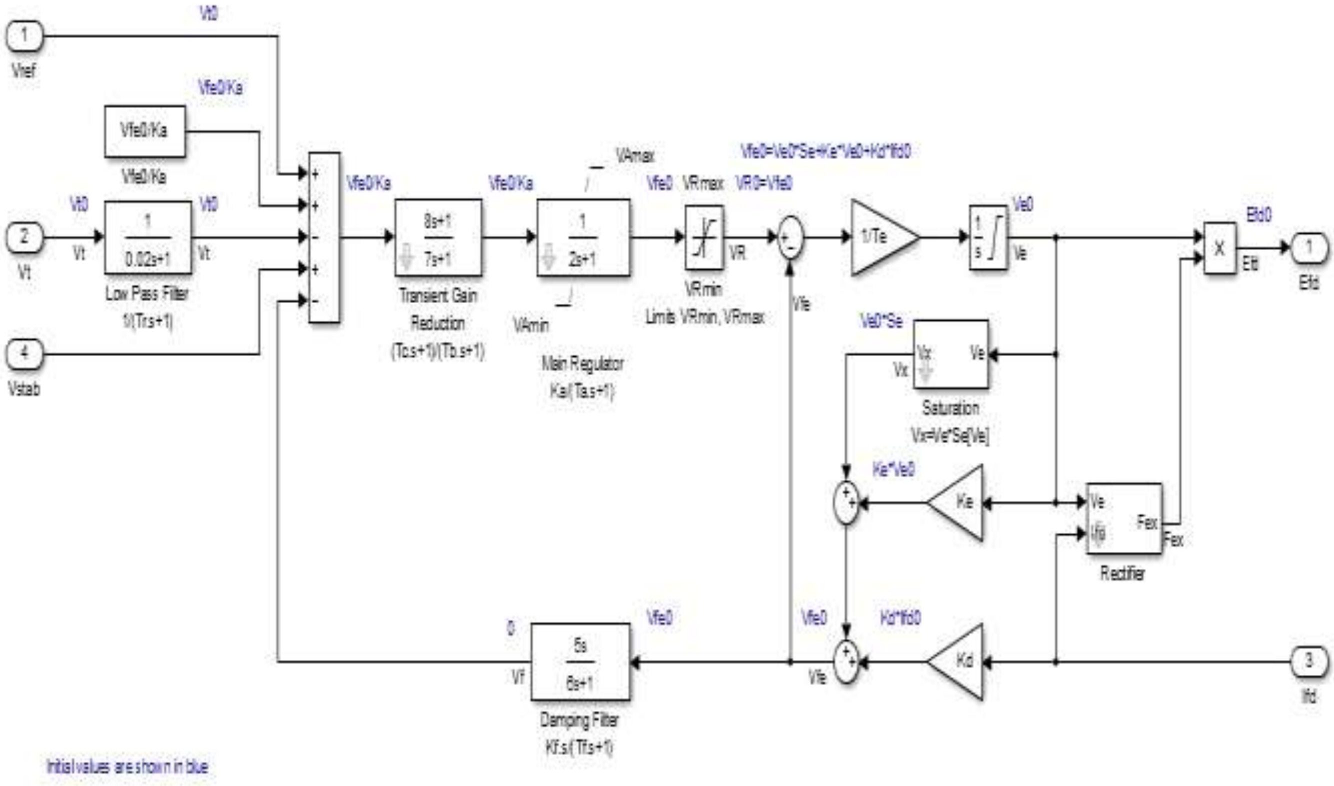

Fig. 3: Block Diagram of AC1A AC Exciter.

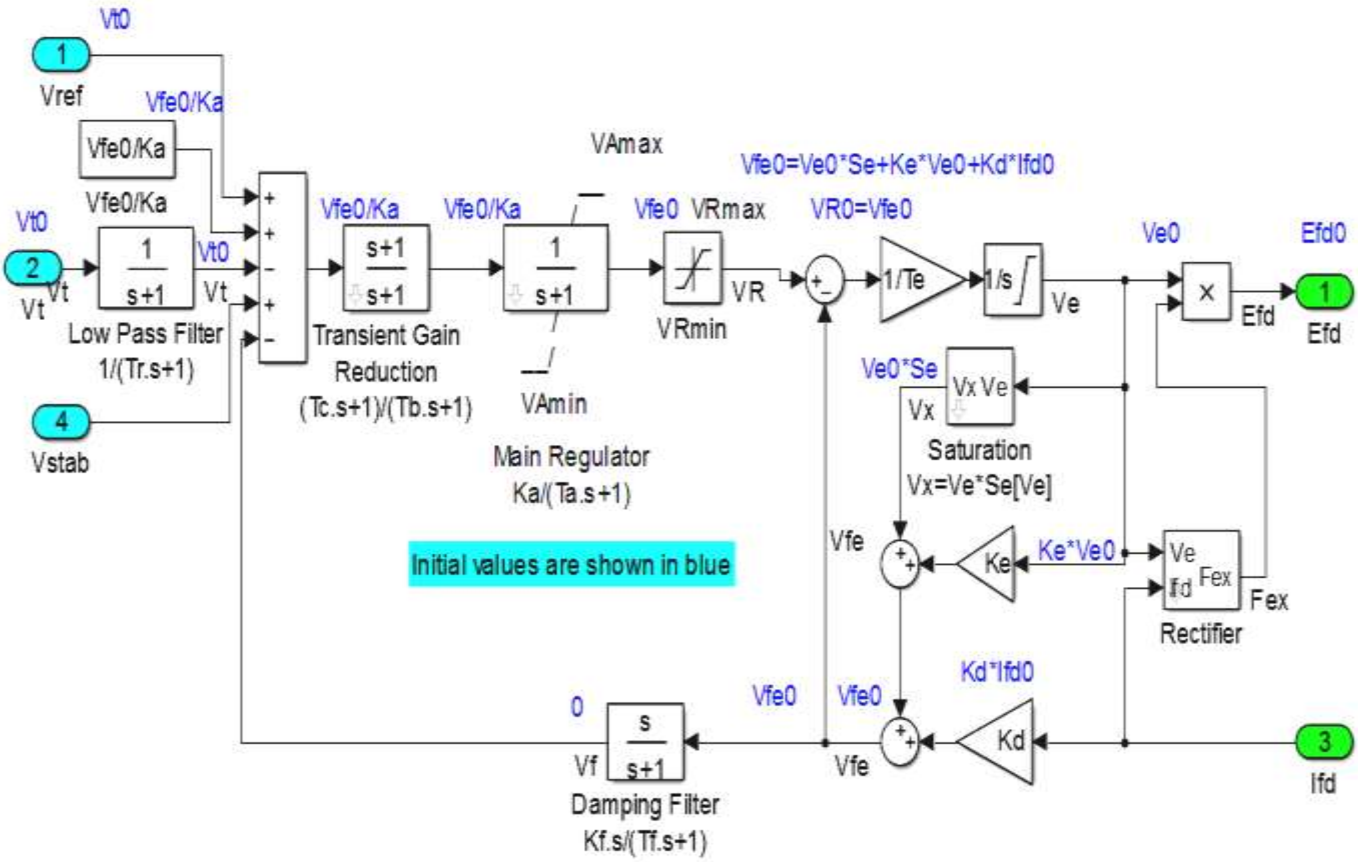

Fig. 4: AC15 excitation system.

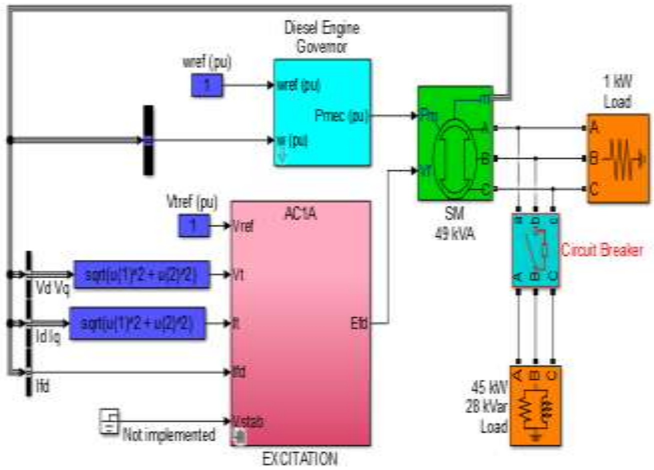

Fig. 5: 49 kVA natural gas generator in Matlab (Off-grid).

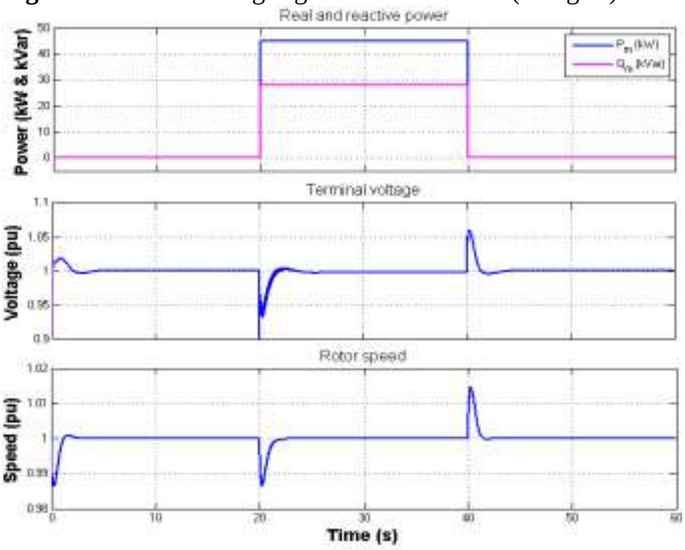

Fig. 6: Power, voltage, speed and time curve.

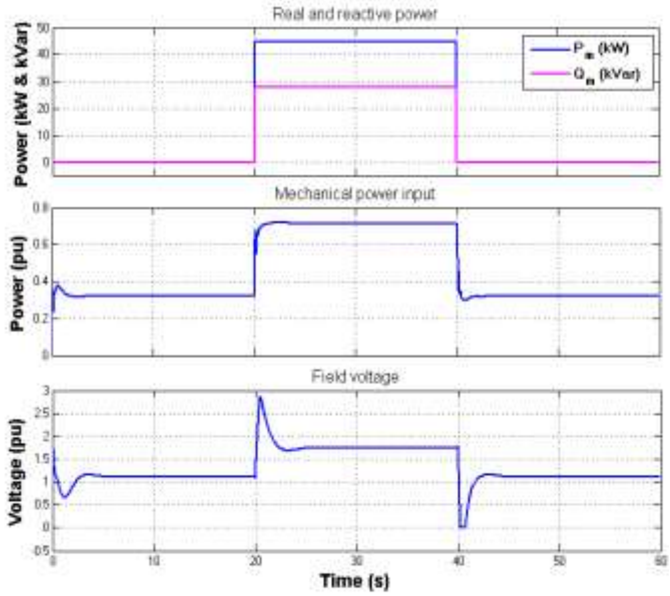

Fig. 7: Power (Mechanical, Reactive), voltage and time curve.

C. Grid tied Operation

A 50kVA natural gas generator for the grid connected system is modeled and simulated using MATLAB/Simulink and presented in figure 8. The performance, output characteristics, the speed of the generator, kV output, the real and reactive power from the simulation results are presented in figure 9, 10, and 11.

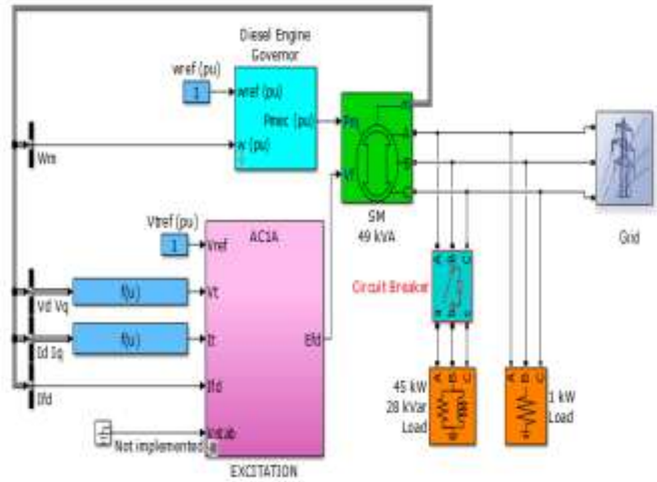

Fig. 8: 50 kVA natural gas generator in Matlab (Grid tied).

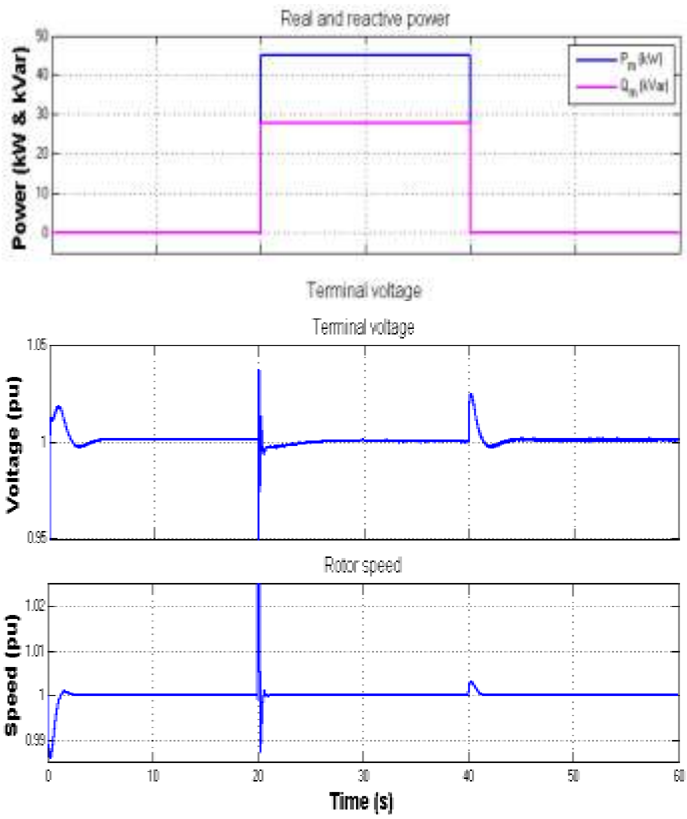

Fig. 9: Power, Voltage, speed and time curve for grid tied operation.

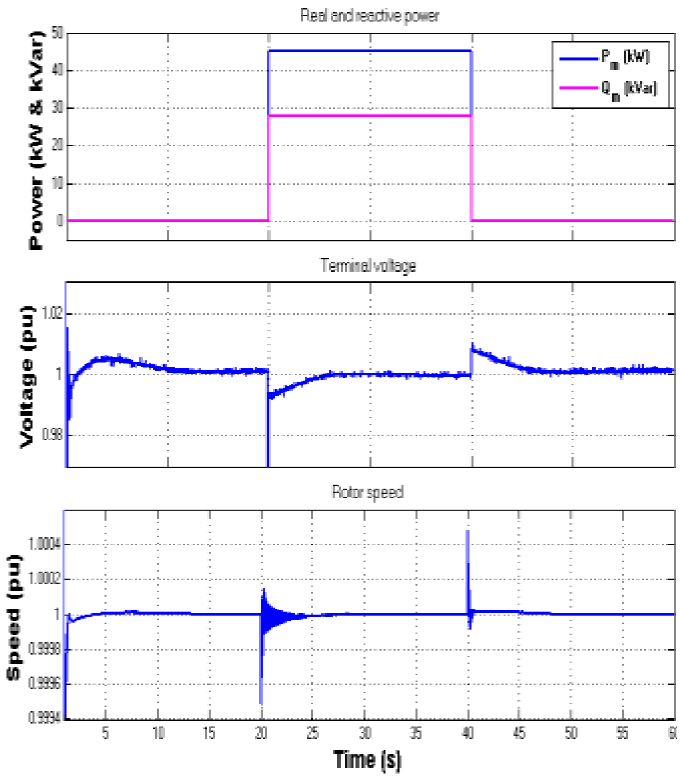

Fig. 10: Power, voltage speed and time curve for grid tied operation.

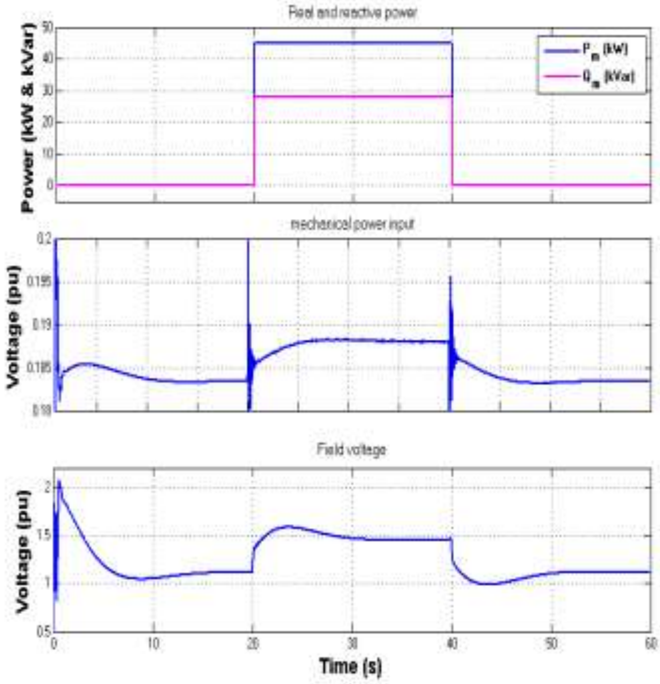

Fig. 11: Power (Mechanical, Reactive), voltage and time curve.

In the case of grid tied operation, the switching operation of load at 20th and 4th second is smoother than the off-grid operation, the output voltage fluctuates between 105% to 95% of rated output within a very short transient time compared to the off-grid, the settling time is less than the off-grid system, system attains stability very quickly, and the generator terminal speed remains almost constant.

*D. Combined Heat and Power Generation (CHP)***:**

To reduce the world wide CO_2 emission, the enhancement of the fuel efficiency is an excellent solution. The cogeneration or combined heat and power (CHP) is a promising technology to fulfill the demand and it uses the heat engine or power station to generate electricity and useful heat energy at the same time. The comparison of fuel efficiency between conventional and using CHP technology is presented in figure 12.

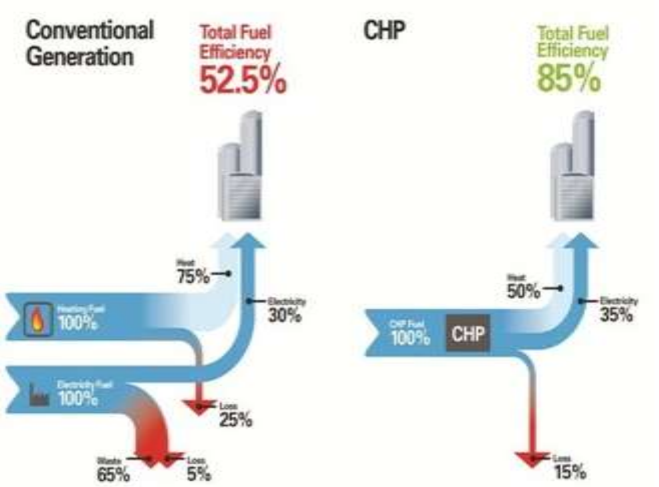

Fig.12: Conventional generation vs CHP.

4. Modeling CHP Generator

A Matlab/Simulink model of the CHP system is presented in the figure 13, each block represents a suitable transfer function in which the system input interacts with the environment is independent of the system internal variables. The fuel power is used as the system input where the electrical and thermal power are the output, and the active and reactive power can be calculated from the electrical power using a suitable power factor. The power map for 24 hours' time from the simulation result is shown in the figure 14. From the figure, the fuel power is taken as 30 kW, the electrical and thermal power output are gained as 7 kW and 18.5 kW respectively. The performance and efficiency of CHP plant can be found as 85% as illustrated in figure 12.

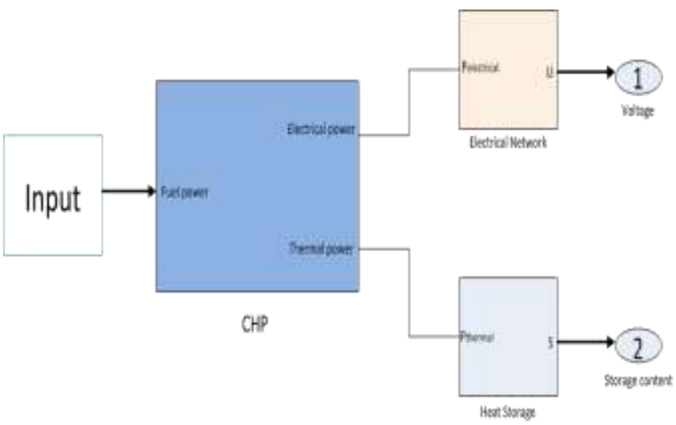

Fig.13: Model of the CHP.

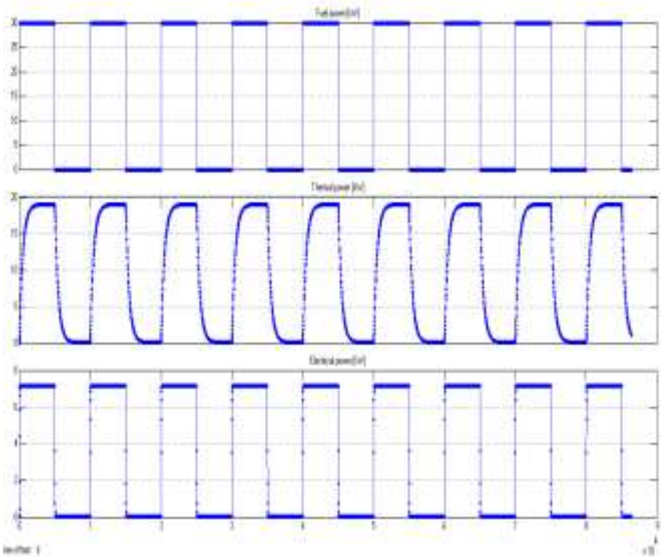

Fig. 14: Performance of CHP plant.

5. Electric Vehicle Charging Station

Here, a charging station expected to be accomodated near a distribution node area. is outlined. Not only aborbing the power from the grid to charge itself, the electric vehicles connected to the charging station will also support the utility grid or the microgrid from the storage system, if it requires. This support from the electric vehicle to the grid is commonly known as V2G support. In this support, for peak shaving, voltage, and frequency stbility, the grid system can take the advantages of the excess amount of energy stored in the batteries [3]. A V2G enabled charging station is illutrated in the figure 15.

A. *Electrical Vehicle Charging Station levels:*

Electrical vehicle Charging Stations offer different levels of power depending upon the length of the required charge. The technical specifications of the electrical vehicle charging station is given at table 2.

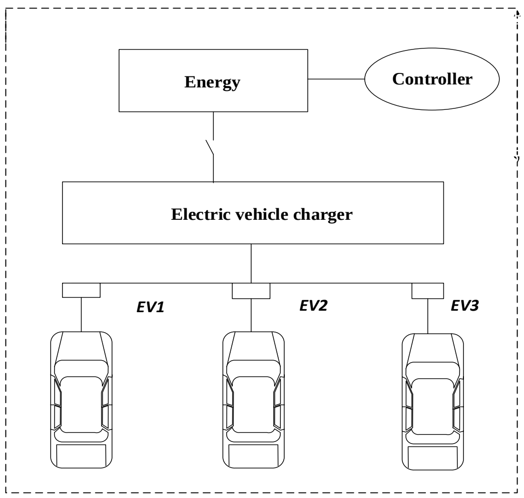

Fig. 15: Electrical Vehicle Charging Station.

Table 2: Technical Specifications of Electrical Vehicle Charging Station.

Level	Voltage	Current (Amps)	Power (kVA)	Phase	Standard Outlet
1	120	12	1.44	Single	NEMA 5-15R Standard 110V US outlet
2*	208/240	32/30	6.7/7/7	Single	SAE J1772/3
3	480	400	192	Three	No Standard

Charging time reduction is one of the cardinal objectives to make the electric vehicles more user-friendly. In that case, the fast DC charging can offer an appreciable opportunity [1]. In practice, it allows to reduce charging times from 10 to 20 minutes. A DC fast charge station, converting 480 VAC 3 phase electrical power into the 400 VDC, allows EV drivers to charge their vehicle in 15-30 minutes. The charging power is classified into three different levels based on the US National Electrical Code 1999 and SAE International standard as shown in Table 3. A variety of aspects needs to be taken into account when designing the circuit of the charging station. Here, the DC charging station configuration (proposed) is illustrated in the figure 16. According to this illustration, the inverter is interfaced to the network through an LCL filter and a transformer. There, a single DC bus feeds all the individ ual battery chargers [1]. Apar form the charging station, the vehicle to grid connection at National Renewable Energy Laboratory is depicted in figure 17.

Table 3: Classification of charging power.

Levels	Detail	Charging Voltage	Charging Current	Charging Power	Charging Time	Application Area
1	120 V Single phase AC outlet (on-board vehicle charger)	120 VAC	12-16 A	1.4-1.9 kW	BEV: 17hrs(SOC-20% to full) PHEV: 7hrs (SOC-0% to full)	Home
2	208-240 V Single phase AC outlet (on-board vehicle charger)	240 VAC	15-80 A	3.3-20 kW	BEV: 7hrs(SOC-20% to full) PHEV: 22hrs (SOC-0% to full)	Home
3	200-450 V single phase DC outlet (off-board vehicle charger)	240 VAC	30-200 A	45-90 kW	BEV: 10 min. (SOC-0% to 80%) PHEV: 20min. (SOC-20% to 80%)	Home/Public
4	200-600 V three phase EVSE DC outlet (off-board vehicle charger)	480VDC	167-400 A	45-240kW	BEV (only) :<10 min. (SOC-0% to 80%)	Public
BEV: Battery Electric Vehicles, EVSE: Electric Vehicle Supply Equipment, PHV: Plug-in Hybrid Electric Vehicle, SOC: State of Charge						

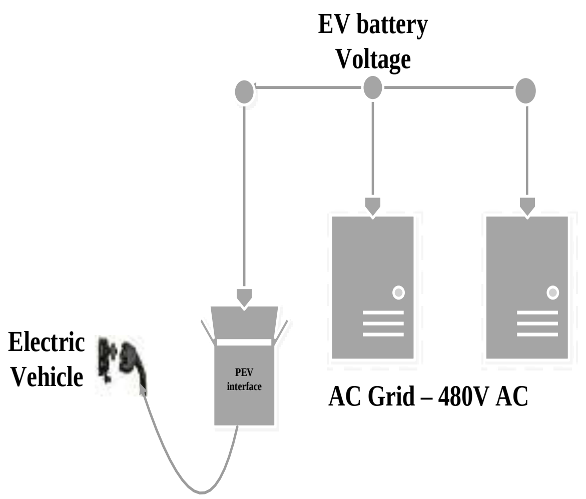

Fig.16: EV Charger Testing and Integration Facility with Power Electronics Interface.

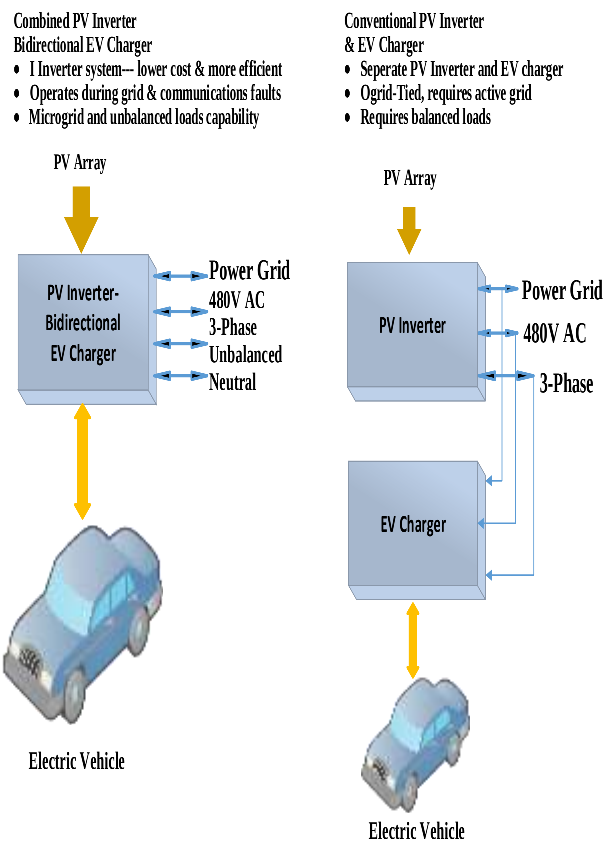

Fig. 17: Vehicle to Grid connection at National Renewable Energy Laboratory.

B. DC Bus Capacitance Calculation

The size of the DC capacitance size has direct influence on the DC bus stability. Actually, it is required to support the DC current ripple. With the number of the EV chargers to be connected to the DC bus, the ripple current will be increased. Hence, the DC capacitance calculation is required. The DC capacitance is determined as follows by the capacitor energy rate of change during the transients and the rated active power [1].

$$C_{dc} = \frac{S_{rated}}{V_{dc}{}^{2}} \frac{2nT\Delta r\cos\phi}{\Delta x} \qquad (24)$$

Where,
T= Period of AC voltage waveform,
n= Multiple of T,
Δr= DC power range of change in percent during transients,
Δx= Allowable DC bus voltage range of change in percent during transients.

C. EV Battery

In the figure 18, the battery model electric circuit configuaration is illustrated. In this illustration, V_{oc} is the open circuit voltage. The open circuit voltage necessarily depends on the SOC (State of Charge). Here, the voltage-current characteristic is modeled by a series resistance R_{series}. Besides that, the RC parallel circuit represents the transient response of the battery [1].

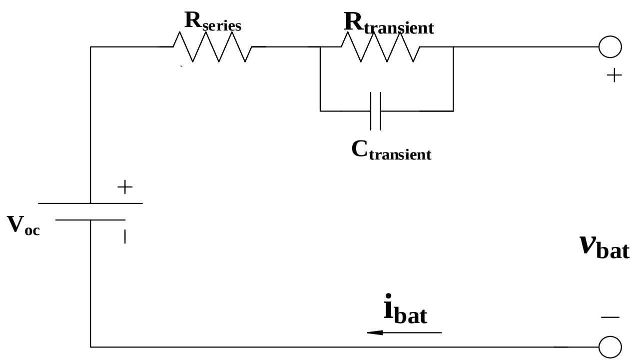

Fig. 18: Thevenin battery model [1].

D. Battery Charger

In figure 19, the battery charger is modeled below. It necessarily consists of a bi-directional DC-DC converter with two IGBT switches. These are operated by the complimentary control signals. Here, when the lower switch is operated, the converter immediately boosts the left side voltage v_{bat}. Then, the current i_{bat} in the inductor L_{bat} flows to the capacitor C. On the other hand, when the upper switch is operated, the converter, in that case, acts as a buck-type converter and i_{bat} flows from capacitor C to the inductor [1].

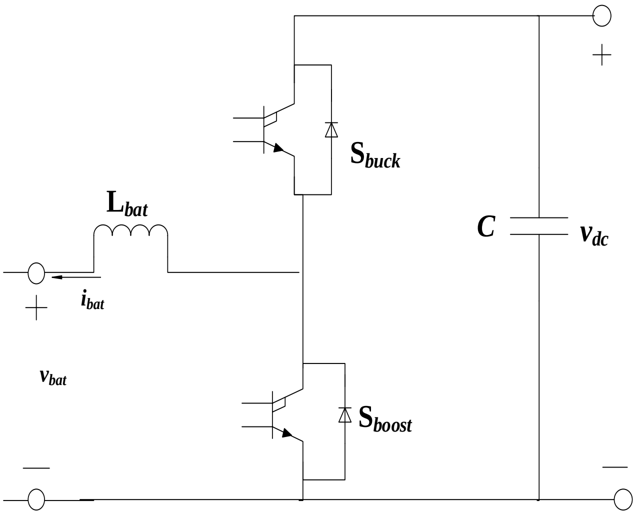

Fig.19: Battery charger configuration.

E. Three-phase inverter

The three phase inverter configuration is illustrated in the figure 20. In this depiction, the inverter is eventually connected to an LCL filter.

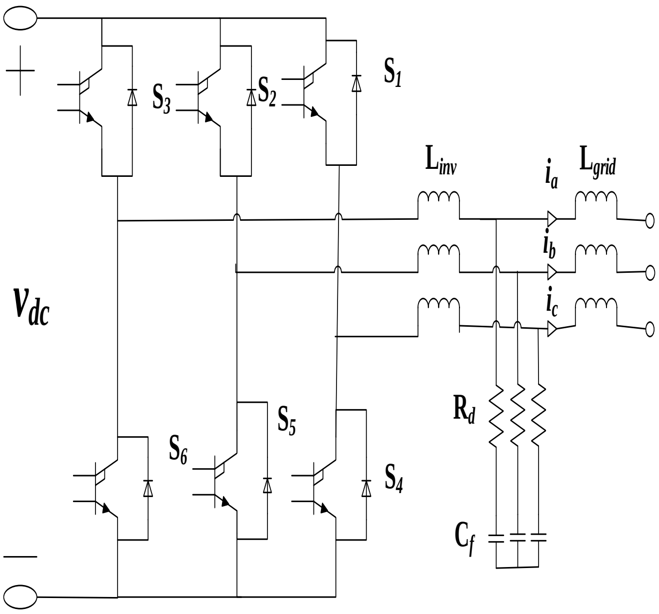

Fig. 20: Three-phase inverter plus LCL filter [1].

F. *LCL Filter:*

Generally, the selection of the inverter side inductance is based on the DC voltage, inverter modulation index, switching frequency, and THD (Total Harmonic Distortion). However, the capacitance and grid-side inductance basically depend on the reactive power, grid parameters, resonance frequency, and the ripple attenuation factor [1]. The inverter side inductance L_{inv}, filter capacitance C_f and grid side inductance L_{grid} can be determined by using the equations (25), (26), and (27) respectively:

$$L_{inv} = \frac{V_{grid}^{2}}{S_{rated}.THD.2\pi f_{sw}} \sqrt{\frac{\pi^2}{18}\left(\frac{3}{2} - \frac{4\sqrt{3}}{\pi} m_a + \frac{9}{8} m^2{}_a\right)} \quad (25)$$

$$C_f \le \frac{0.05 S_{rated}}{2\pi . f_{grid} . V_{grid}^{2}} \quad (26)$$

$$L_{grid} = \frac{RAF + 1}{RAF . C_f . 2\pi f_{sw}^{2}} \quad (27)$$

6. Simulation and Results

There are three constant current loads with 50-60A at 208V single phase or 480V three phase available at university of Wisconsin-Milwaukee. Figure 21 presents the schematic diagram of the three phase supply integration to the grid from the renewable sources including the basic configuration of the electric charging station using renewable energy sources.

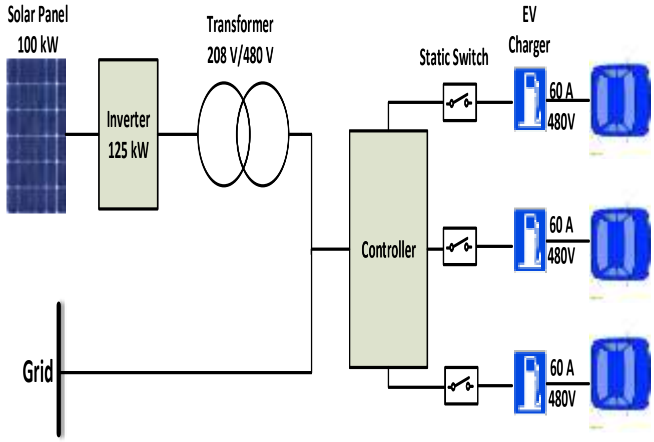

Fig. 21: EV charging station.

After that, figure 22 depicts the proposed Simulink model of the EV battery charging station along with its components for the microgrid integration. Characteristics of the EV charging current with time of the proposed model is presented in the figure 23. Here, the charging current is fluctuating and not constant for the overall operation of the station.

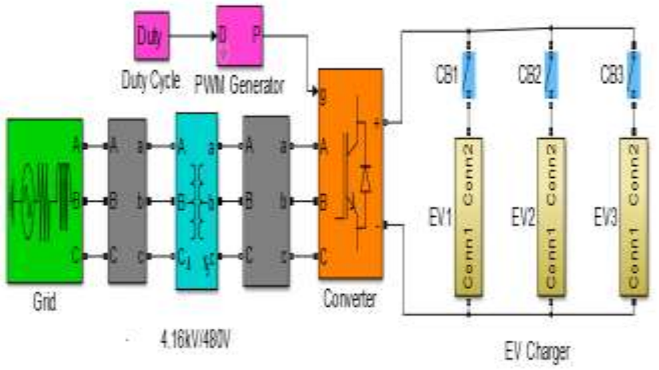

Fig. 22: EV battery charging model in simulink.

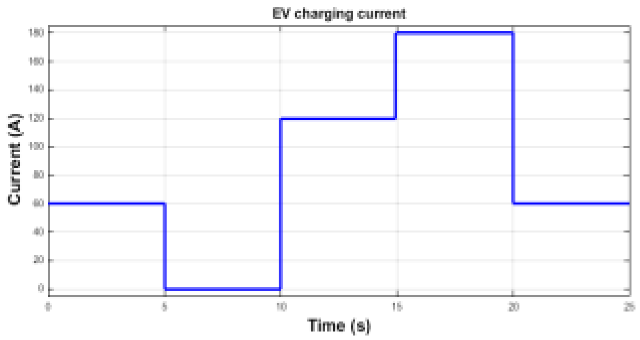

Fig. 23: EV charging current characteristics.

For the testability of aforementioned model, a simulation platform is created for the case study using MATLAB/Simulink. The schematic representation of the overall system is presented in the figure 24. For the simulation purpose, two 45kW natural gas generators are modeled as mentioned in the figure 8 and used in the Grid Tied Mode of operation of the microgrid systems. The simulation is carried out for 1.5 second of time and the load profile is depicted in the figure 25.

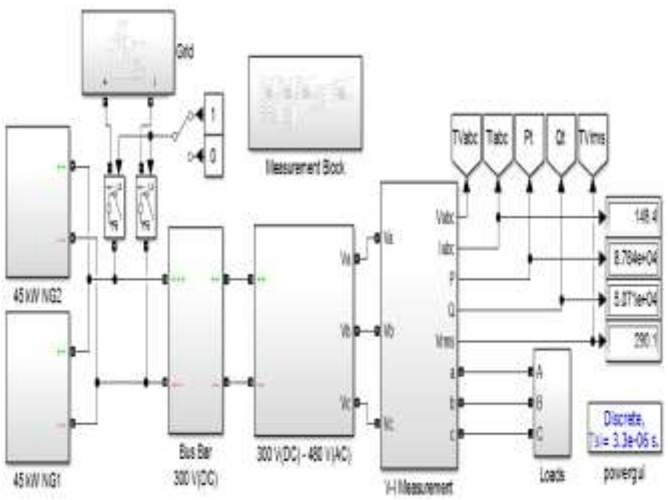

Fig. 24: Schematic Representation of Microgrid System.

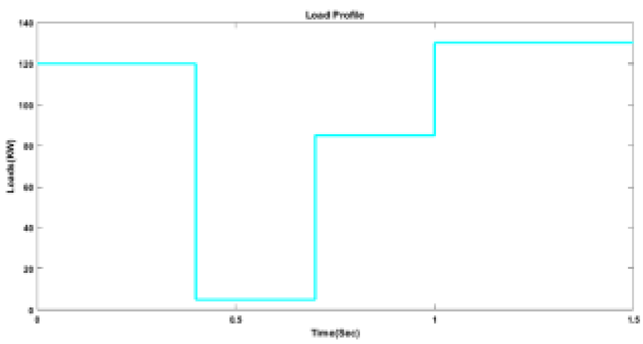

Fig. 25: Load Profile.

The simulations are carried out for the different loading condition, overload, very low load, medium, and high load. Natural gas generators in the microgrid system are used as backup generator unit with other integrated renewable sources like the wind energy, solar energy, ocean wave energy converter (OWECs), and the geothermal energy. Due to the high cost of the natural gas, they are only operated in the urgent need for the additional support. In the simulations presented here, two unit of 45kW natural gas generators are used tied with the power grid. The voltage and current characteristics for both the NGs and Grid are presented in the figure 26 below. At the time of overloading from 0 to 0.4 and 1 to 1.5 sec of simulation, the additional power is drawn from the power grid as shown in figure 27. Whenever, the natural gas power generation exceeds the supply demand, the additional powers provides the feedback to the power grid.

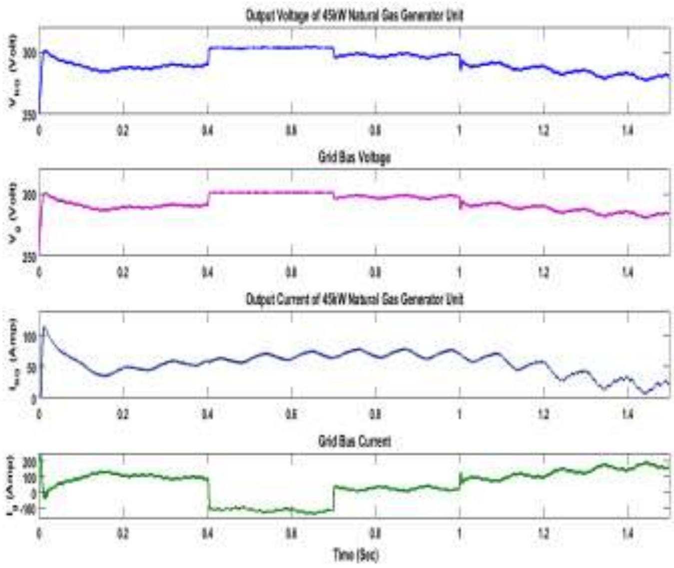

Fig. 26: (a) Output Voltage from Natural Gas Generator (b) Grid Bus Voltage (c)Output Current of NG unit (d) Grid Bus Current in Grid Tied Operation of Microgrid.

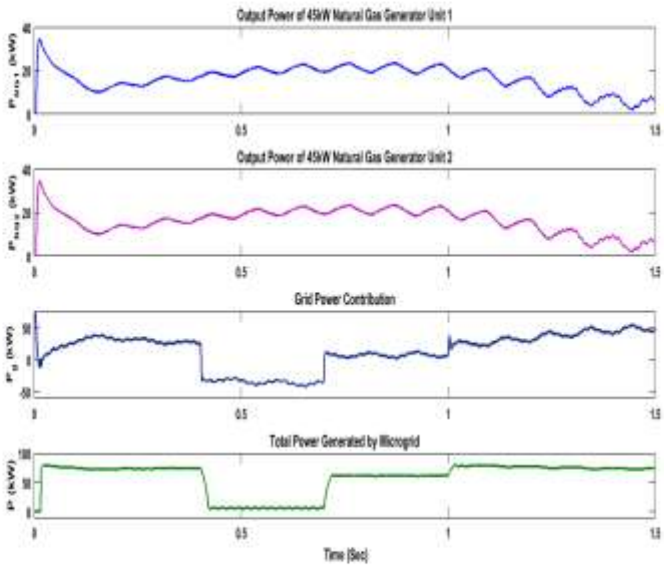

Fig. 27: (a) Output power of NG unit one (b) Output power of NG unit two (c) Output power of the grid (d) Overall power generated by microgrid.

To eliminate the harmonics and frequency mismatch, all the sources in microgrid are coupled with a 300V DC bus and further this dc voltage is converted to 480 V three phase AC using a 300V DC to 480V AC inverter coupled with the distribution network. The voltage and current characteristics from the distribution side are illustrated in the figure 28.

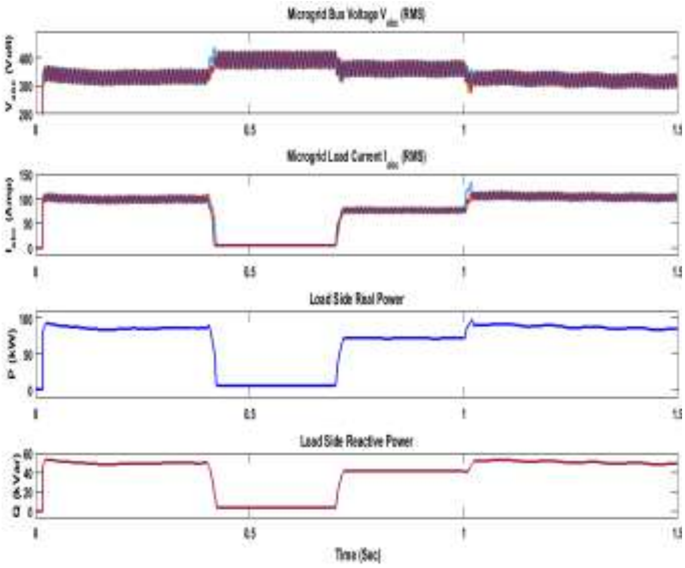

Fig. 28: (a) Microgrid bus voltage (b) Microgrid load current (c) Real Load Power (d) Reactive Load Power.

7. Conclusion

To meet the demand of the next generation power system, to reduce the carbon emission, and save the environment, renewable and clean energy resources can be the fuel of choice. In this paper, firstly, the entire microgrid model has been presented. Later, the natural gas generator modeling has been presented including the excitation systems, off-grid operation, grid-tied operation, combined heat and power generation. Next, the modeling of the Combined Heat and Power generation (CHP) has been delineated. After that, the EV charging station modeling has been presented including the electric vehicle charging station levels, DC bus capacitance calculations, EV battery, battery charger, three phase inverter, LCL filter. Finally, the simulation and analysis have been delineated for certain parameters of the natural gas generaotors in the microgrid systems. All the results have been verified by the Matlab simulations meticulously.

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