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Investigation and Comparison of DC and AC Nanogrid Networks using MATLAB/Simulink

Farrukh ibne Mahmood[1], Muhammad Zain Ul Abideen Afridi[2], Hamza Ahmad Raza[1], Hassan Abdullah Khalid[1]
[1]USPCAS- E National University of Sciences and Technology, Islamabad, Pakistan
[2]USPCAS- E University of Engineering and Technology, Peshawar, Pakistan

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***Abstract*—** This paper performs a simulation-based analysis on a DC and AC nanogrid network based on various case studies. Since the use of DC devices has increased, such as laptops, cell phones, LED TVs, etc., this study aims to demonstrate that DC nanogrid systems are better than their AC counterparts in terms of energy efficiency. An architecture for both DC and AC nanogrid is modeled in MATLAB Simulink. Both designs constitute a PV system with a grid-tied inverter, an electric vehicle, and various common domestic loads. A set of case studies are performed on both networks to validate that DC nanogrids are better due to fewer energy losses. Furthermore, an economic analysis is also performed to ascertain the viability of both networks. The simulation results confirm that the losses in a DC nanogrid are less than in an AC nanogrid. Moreover, the DC system can be more economical as well which establishes that DC nanogrid systems should be preferred to AC systems to ensure energy efficiency. The results of this study can be used for modeling future nanogrid systems.

***Keywords*—** Nanogrid, Microgrid, DC, AC, Energy efficiency, Energy loads, Renewable energy.

I. INTRODUCTION

With the advent of urbanization and a continuous increase in the world population, global energy demand has increased. Furthermore, the environmental damage due to prolonged use of fossil fuels and the limited time for which the fossil fuels can be used has led to the use of renewable sources of energy [1], [40], [41]. Although renewable energy sources provide an attractive means to generate power without polluting the environment, issues such as intermittency linked to renewable sources have impeded their development [2]. Due to the unreliable nature of these sources, they have to be used in conjunction with other sources. Therefore, their use is preferred in distributed generation. For efficient utilization of distributed generation, nanogrid systems can be formed. A nanogrid is a system with a bus in which various generators and loads are connected [3]. These nanogrids can be either DC or AC. Since, at present most loads being used are DC (Laptops, cell phones, TVs etc.) [4], the use of DC nanogrids has gathered impetus. Therefore, in the future, electrical systems will have more DC appliances.

Furthermore, DC systems offer several advantages over AC systems in terms of efficiency, power quality, and reliability. These advantages include no reactive power in DC, making it more efficient than AC. 50% of loads used in buildings are now DC; using a DC nanogrid would exclude redundant converter stages, increasing the efficiency of the overall system. The use of PV in residential buildings has exponentially increased, therefore, using a DC nanogrid for the distribution of energy by DC sources is more convenient [5].

When comparing AC and DC nanogrids, most of the literature agrees that DC nanogrids are better in terms of efficiency as there are fewer power conversion, Also, most renewable energy sources, storage systems, and household loads (laptops, cell phones, etc.) are DC. However, the articles also focus on that fact that at present households are constructed to operate on AC as the National Grid supplies AC. Hence, modifying an existing building to DC is a costly endeavor. Nevertheless, making a new house to operate on a DC nanogrid network is very much feasible [6]. Moreover, some research papers have presented the idea of a hybrid AC/DC nanogrid in which a DC distribution system is coupled to the existing AC network [7]. Furthermore, numerous articles have also proposed interconnection of nanogrids known as a microgrid, a network that could allow power-sharing between the connected nodes [8]. Consequently, most recent nanogrid literature focuses on network design, hardware, and control in nanogrids [6] and little literature is focused on the comparison between both AC and DC nanogrid systems.

Threofore, in this paper, a comparison between a DC and AC nanogrid is made to provide substantial data to support that DC nanogrids offer a better solution in terms of energy efficiency. A DC and AC nanogrid network consisting of a grid-tied inverter, an electric vehicle, a PV system, and a house comprising various domestic loads was modeled in MATLAB Simulink. The house was modeled on the concept of a modern home and included six domestic appliances: LED light, LED TV, Air conditioner, Fan, Laptop, and a Refrigerator [9]. For the DC nanogrid, all loads used are DC, while for the AC nanogrid, LED light, LED TV, and Laptop are DC loads, while Fan, Refrigerator, and Air conditioner are AC loads. All loads are modeled based on commercially available products. To demonstrate energy efficacy, a detailed loss analysis is performed on both networks using 6 case studies, 3 for the DC network and 3 for AC. An economic analysis is also performed to determine the feasibility of both networks. The results of both studies are compared and the DC nanogrid shows a significant advantage in terms of efficiency and economy over its AC counterpart.

II. SYSTEM MODELING

A. DC Nanogrid

The DC nanogrid architecture modeled in Simulink is shown in Figure 1. The main components in the DC nanogrid are as follows:

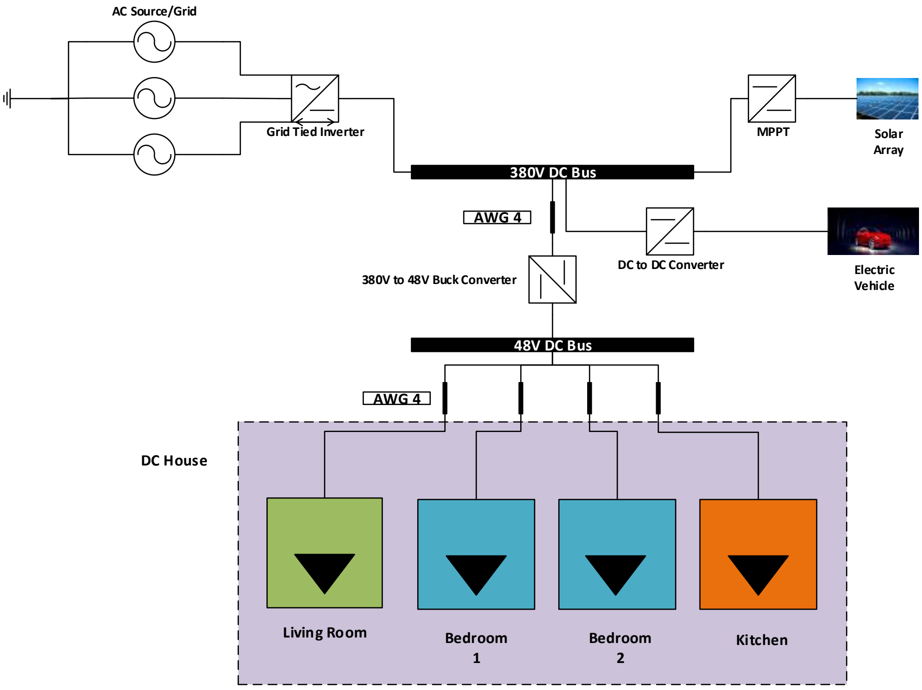

Figure 1. DC Nanogrid Design

Grid-tied inverter, solar photovoltaic system with MPPT, electric vehicle, 380V DC bus, 380V to 48V buck converter, AWG 4 wiring between 380V DC bus and buck converter, 48V DC bus, house consisting of four blocks (Living room, bedroom 1, bedroom 2, kitchen), all loads in the DC nanogrid house are DC loads and four AWG 4 wires connecting the 48V DC bus to the four blocks in the house.

Both the national grid and solar photovoltaic system feed the 380V DC bus. The grid-tied inverter converts the incoming AC from the National grid to DC. The EV is also connected to the 380V DC Bus and is charged and discharged through a buck/boost converter. A buck converter at the output of the 380V bus steps down and regulates the voltage to 48V at the 48V DC bus. All the house loads are connected to the 48V DC bus, with separate wiring for each block. Each house block consists of various domestic DC appliances which are connected to the 48V DC bus. Two cases are defined for power distribution in the nanogrid as follows:

1) Using the 380V DC bus for distribution (single wire between 380V bus and buck converter)
2) Using the 48V DC bus for distribution (four wires connecting each house block with the 48V bus) For both cases, peak current was determined, and AWG 4 wire of length 15.2 meters was selected [10].

Table 1. Wire Parameters [11]

AWG	Diameter (mm)	Area (mm)	Resistance (Ω/km)
4	5.189	21.2	0.815

The wire is modeled using a resistor and the resistance is calculated by the following relationship:

$$Resistance = Resistance\left(\frac{Ohms}{km}\right) * Wire\ length\ (km) \qquad (1)$$

B. AC Nanogrid

The AC nanogrid architecture modelled in Simulink is shown in Figure 2.

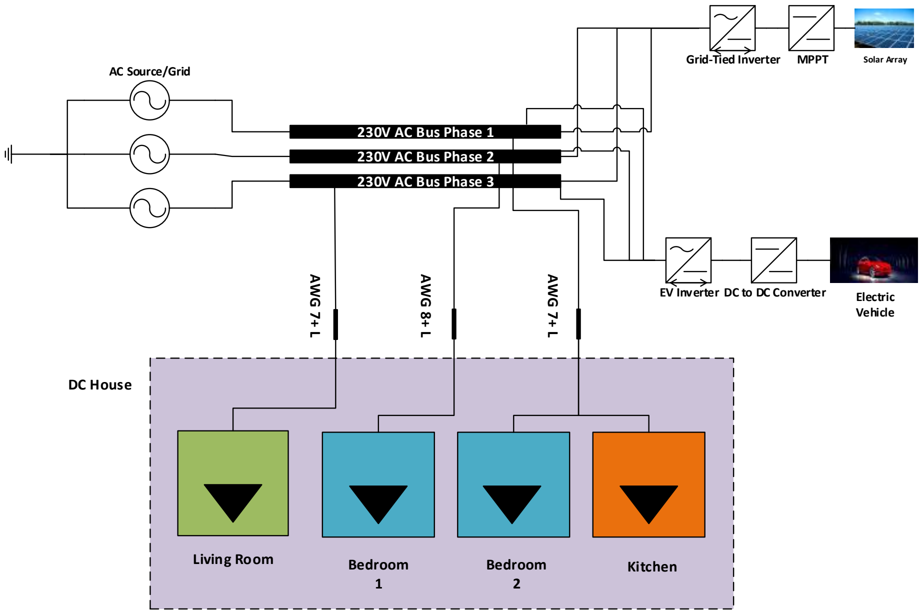

Figure 2. AC Nanogrid design

The main components include grid-tied inverter, solar photovoltaic system with MPPT, electric vehicle, 230V AC bus (one for each phase), AWG 7 and 8 wiring between the AC bus and house, house consisting of four blocks (living room, bedroom 1, bedroom 2, kitchen), various domestic loads within each house block which are both DC and AC. Both the national grid and solar photovoltaic system feed the 230V AC bus. The grid-tied inverter converts the DC output from solar PV to AC. EV is also connected to the 230V AC bus and an inverter/rectifier converts the incoming AC to DC or vice versa. The EV is then charged or discharged through a buck/boost converter. There are three 230V AC buses, one for each phase. From phase 1 AWG 7 wire is used to connect the house and from phase 2 and 3, AWG 8 wire is used for connecting the house. The house contains both DC and AC loads. Those DC loads are used which have no AC counterparts available commercially, these include a laptop, LED light and LED TV. The AC loads present in the house are a fan, refrigerator, air conditioner and a miscellaneous load. The loads in the AC nanogrid are selected in such a way so that a fair comparison can be done between the DC and AC network. For DC loads AC output is converted to DC using a rectifier and then the voltage is regulated using a DC-DC converter. AWG 7 and AWG 8 wire of length 15.2 m were selected after measuring the peak current on all three phases.

Table 2. Wire Parameters [11]

AWG	Diameter (mm)	Area (mm)	Resistance (Ω/km)
7	3.665	10.5	1.634
8	3.264	8.37	2.060

Since this is an AC network the wire is modeled using a resistor and an inductor. The resistance is calculated by the relationship given in (1). Line inductance was calculated using wire diameter and wire length [12].

C. PV Array

Both the DC and AC Nanogrid have a PV system comprising of 7 modules connected in series. The modules used are 1Soltech 1STH-35-WH with the following performance parameters. Voc=51.5V, Isc=9.4A, Vmp=43V, Imp=8.13A and Maximum Power=349.59W. The total system rating is 2.45KW [13].

The temperature for the PV array is set at 25°C. The data for Irradiance was obtained from Metrological High Precision Station mounted in NUST Islamabad. From the solar data, an average irradiance was calculated for summer months of May and June for peak hours i.e., from 9 AM to 3 PM [42], [43]. The calculated average value of 816W/m2 is used as the irradiance for the solar array in MATLAB.

The PV array is connected to a boost converter which extracts maximum power from the modules using the incremental conductance MPPT technique. For the DC nanogrid the power from the PV system is fed to a 380V DC bus and for the AC nanogrid the power is converted to AC and fed to a 230V AC bus.

D. Grid-tied Inverter

The grid-tied inverter is modeled using a 3 level IGBT bridge being controlled by a PWM in the inverter control. The inverter maintains the DC bus voltage at 380V, and the carrier frequency is set at 5000Hz with the system frequency at 50Hz. The inverter controller is made of 4 main components the voltage regulator, current regulator, phase lock loop and a PWM generator. The voltage regulator determines the active current reference for the current regulator. The current regulator then determines the required reference voltage using active and reactive current references (in this model the reactive current reference is zero). The phase lock loop allows for synchronization and values of voltage and current for the current regulator. The PWM then generates pulses according to the required reference voltages to IGBT gate. Figure 3 shows the inverter control implemented in MATLAB.

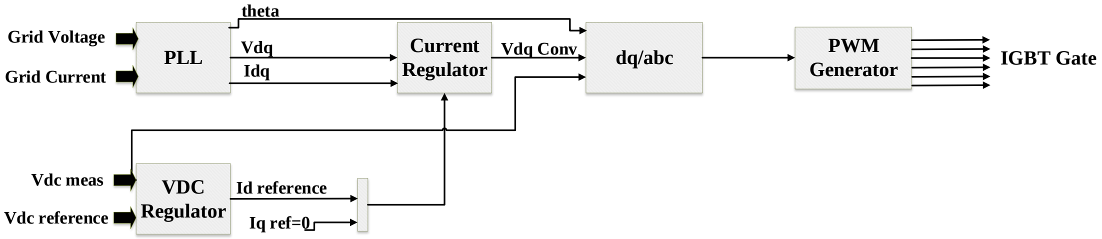

Figure 3. Grid-tied inverter control block diagram

E. *Electric Vehicle*

The electric vehicle (EV) is modeled as a battery in MATLAB. The battery model is based on Tesla's Model S. The battery has an energy rating of 85KWh and a voltage of 375V. When charged at a voltage of 240V the battery takes 4 hours (90A) to charge completely as indicated by the datasheet [14]. The battery is connected to a Buck/Boost Converter. To charge the battery from the DC link the converter operates in buck mode and to discharge the battery the converter operates in boost mode. A state of charge (SOC) upper limit of 85% is set to prevent overcharging and a lower limit of 30% to prevent over-discharging. To prevent the converter and battery from high currents overcurrent protection is also modeled. The overcurrent protection works by limiting the duty cycle of the converter based on maximum charging or discharging current [15].

Figure 4 and 5 show the EV model implemented in MATLAB. Figure 6 shows the buck/boost converter modeled in MATLAB for charging and discharging the battery. When charging signal is on the converter operates in buck mode and when the discharging signal is on the converter operates in boost mode. Figure 7 shows the EV charging and over charging protection circuit. Maximum charging current is compared with the load current and the desired value for maximum charging current is controlled using a PI controller. This generates an upper limit for the duty cycle. For regulating charging voltage, the reference voltage is compared with the load current and the error generated is then compared with the load voltage. The reference voltage is maintained using a PI controller. Then using a saturation dynamic block, the output from the PI controller is compared with the duty cycle limit, generated by comparison of the maximum charging current and load current. This protects the circuit from over charging. The output from the saturation dynamic block acts as an input to the PWM generator which generates pulses according to the required reference voltage to the MOSFET gate.

Similarly, Figure 8 shows the EV discharging and over discharging protection circuit, the mechanism for which is the same as described for the EV charging and over charging protection circuit.

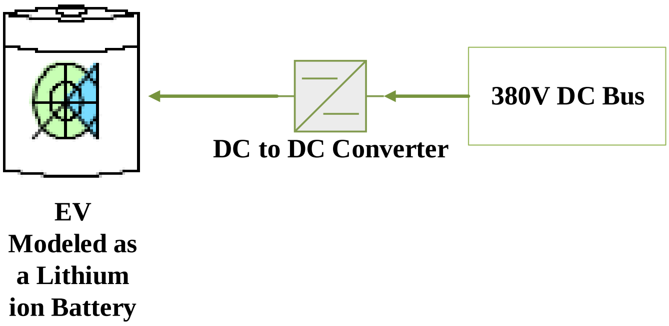

Figure 4. EV in DC Nanogrid

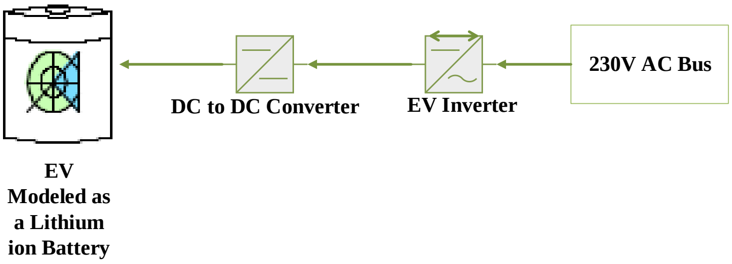

Figure 5. EV in AC Nanogrid

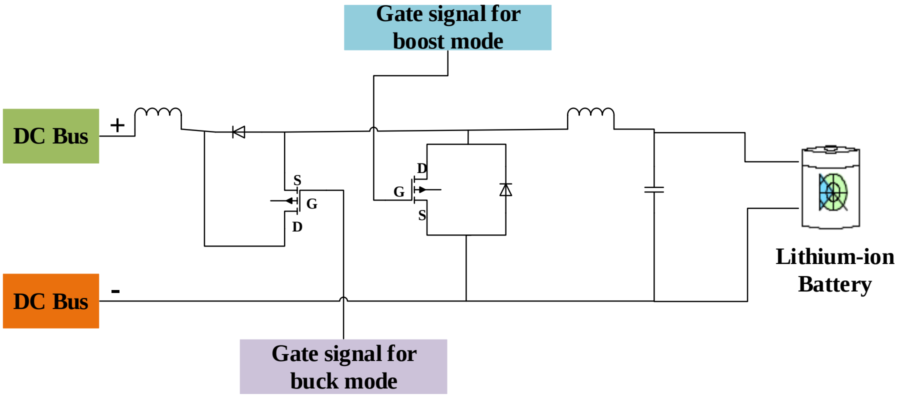

Figure 6. Buck/boost converter for EV

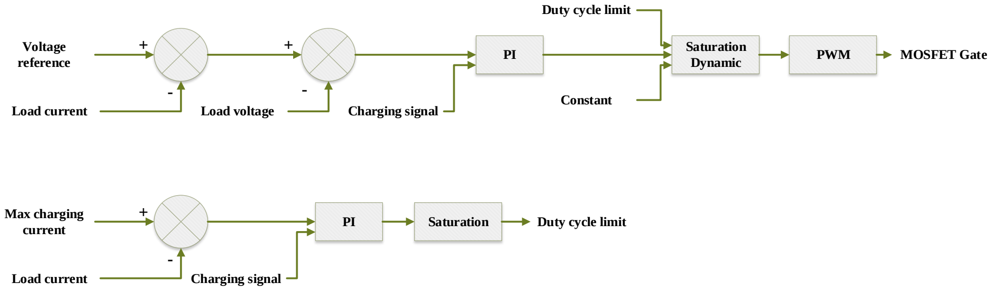

Figure 7. EV charging and over charging protection circuit

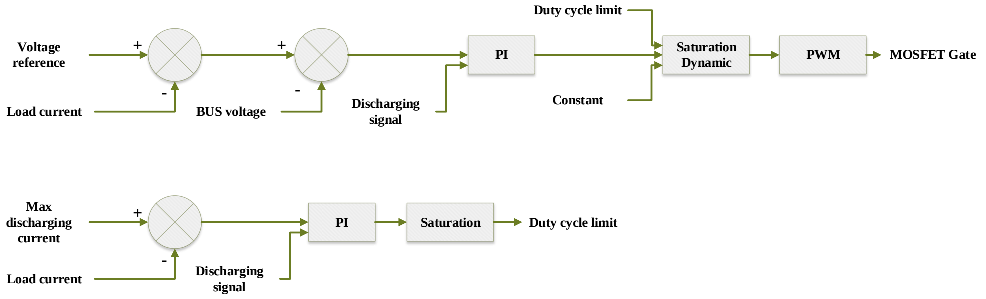

Figure 8. EV discharging and over discharging protection circuit

F. *House Model*

The house consists of four main blocks the living room, two bedrooms, and a kitchen. The loads are distributed within the four rooms as shown in Table 3.

Table 3. Load distribution within the house

Block	LED Light	LED TV	Laptop	Fan	Air conditioner	Refrigerator	Miscellaneous Load
Living Room	✓	✓	×	✓	✓	×	×
Bedroom 1	✓	×	✓	✓	✓	×	×
Bedroom 2	✓	×	✓	✓	✓	×	×
Kitchen	✓	×	×	✓	×	✓	✓

A total of seven DC loads are modeled in the DC nanogrid. These include LED light, LED TV, DC fan, laptop, DC air conditioner, DC refrigerator and a miscellaneous load.

The LED light is modeled based on LED E26 model. The lamp has a working voltage of 45 to 60 volts DC with recommended use at 48V. It consumes 0.21A and has a power consumption of 10W. The LED light has a lumen capacity of 950. The light is modeled using 10 diodes connected in series each having a forward voltage drop of 3.2V. A current limiting resistor is also added in series with the diodes. In the network, the bulb works at 48V with a power consumption of 10W as described in the datasheet. Figure 9 and 10 show the implementation of LED light in DC and AC nanogrid respectively [16].

Figure 9. LED Light in DC nanogrid

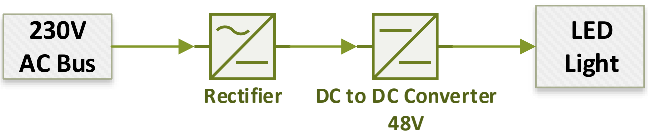

Figure 10. LED Light in AC nanogrid

The laptop is modelled based on Dell Inspiron N5110 model. The laptop works on 19.5V and has a maximum power consumption of 90W and a normal power consumption of 46W which was checked through Intel Power Gadget 3.0. For modelling the laptop two cases were considered, a worst case in which the laptop consumes 90W and a normal case in which the laptop uses 46W. Both cases were modelled using resistors, for the 90W scenario a 4.221-ohm resistor was used and for the 46W scenario an 8.266-ohm resistor was used. Since the laptop is connected to a 48V bus and the working voltage is 19.5 a buck converter is used to step down and regulate the voltage at 19.5V. Figure 11 and 12 show the implementation of Laptop in DC and AC nanogrid respectively [17].

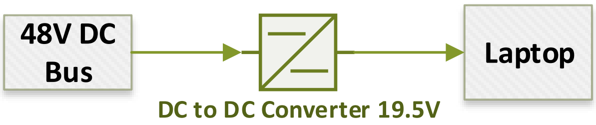

Figure 11. Laptop in DC nanogrid

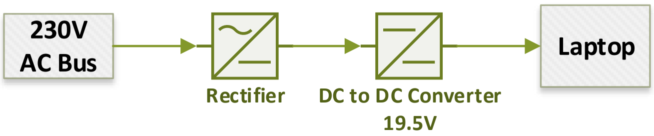

Figure 12. Laptop in AC nanogrid

The LED TV model is based on DC-Powered 21”/24” TV. The TV has a working voltage of 48V and a power consumption of 30W. The LED TV is also modeled using a resistor of 76.8 ohms. Figure 13 and 14 show the implementation of LED TV in DC and AC nanogrid respectively [18].

Figure 13. LED TV in DC nanogrid

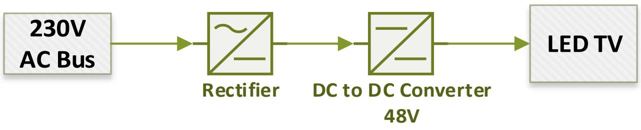

Figure 14. LED TV in AC nanogrid

The fan model is based on 42” ceiling fan which has a working voltage of 24V and a power consumption of 14.4W. A brushless DC motor is used in the fan construction. In Simulink, the fan is modelled using a permanent magnet DC machine. The parameters for the motor are set as described in the product datasheet. Since the fan is connected to the 48V bus and the working voltage is 24V, a buck converter is used to step down and regulate the voltage at 24V.

The refrigerator is modelled using the GEI-90C4 90 litres solar freezer. It has a working voltage of 24V and a power consumption of 60W. It has a cooling performance of -18°C at 30°C ambient temperature. A brushless DC motor is used in the compressor construction. In the study, the refrigerator is modelled using a permanent magnet DC machine and the motor parameters are set as described in the product datasheet. Since the refrigerator is connected to the 48V bus and the working voltage is 24V, a buck converter is used to step down and regulate the voltage at 24V. Figure 15 shows the implementation of both DC fan and refrigerator in the DC nanogrid [19], [20].

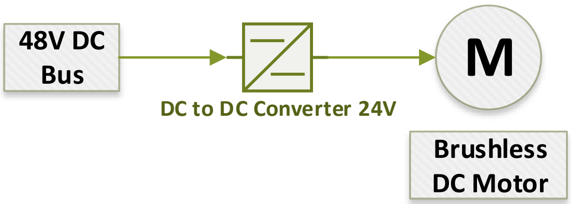

Figure 15. DC fan/refrigerator in DC nanogrid

The air conditioner model is based on HSAC-15C/C DC air conditioner. It has a working voltage of 48V and a power consumption of 770W. The air conditioner has a cooling capacity of 15000 Btu/h. In compressor construction, brushless DC motor is used. In Simulink, the air conditioner is modelled using a permanent DC machine. The motor parameters are tweaked according to the product specification sheet. Fgure 16 shows the implementation of DC Air conditioner in DC nanogrid [21].

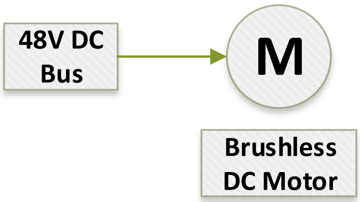

Figure 16. DC Air conditioner in DC nanogrid

The miscellaneous DC load is modelled using a simple resistor. The main purpose of adding this load is to balance power between the four blocks of the house.

Four AC loads are modelled in the AC nanogrid network, a fan, refrigerator, air conditioner and a miscellaneous load.

For a fair comparison between the DC and AC air conditioner such an AC air conditioner is selected which has the same Btu/h (15000) as the DC air conditioner. The air conditioner model is based on DAIKIN K(E) Series (SEER 18) and has a working voltage of 230V and a power consumption of 1250W. A split phase induction motor is used in compressor construction. In Simulink, the split phase asynchronous machine is used to model the air conditioner and the motor parameters are set as specified in the datasheet [22].

Similarly, such an AC fan is used which has the same revolutions per minute (125) as the DC fan. Westinghouse 78545 Hercules ceiling fan with a voltage of 230V and a power consumption of 41W is used to model the fan. The motor used in the fan construction is split phase induction motor and in MATLAB the fan is modelled using a split phase asynchronous machine, using motor parameters as described in the specification sheet [23].

Likewise, an AC refrigerator is selected which has the same cooling performance (-18°C) as the DC refrigerator. The refrigerator model is based on WHF300S2D with a working voltage of 230V and a power consumption of 142W. Refrigerator compressor is made using a split phase induction motor. In Simulink, a split phase asynchronous machine is used to model the refrigerator and the motor parameters are selected as specified in the product datasheet [24]. Figure 17 shows the model for the AC air conditioner, fan, and refrigerator in the AC nanogrid.

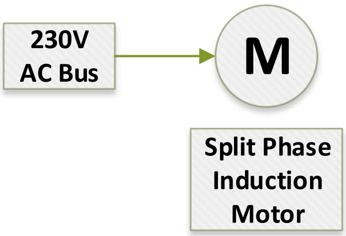

Figure 17. AC air conditioner/fan/refrigerator in AC nanogrid

The miscellaneous AC load is modelled using a simple resistor. The main purpose of adding this load is to balance power between the three phases.

III. SIMULATION RESULTS AND DISCUSSION

A. Case Studies

Three case studies are made as follows to calculate the losses in both networks. Case 1 (Table 4) is load usage from Monday to Friday, Case 2 (Table 5) is for Saturday and Case 3 (Table 6) includes scenarios for Sunday. The losses are calculated for a 24-hour period for each case. Since the scenarios for Monday to Friday are similar, the results include losses calculated over a three-day period (Monday, Saturday, and Sunday).

Table 4. Monday to Friday (load usage)

Time	Living Room	Bedroom 1	Bedroom 2	Kitchen	PV	EV
12 AM to 7 AM	Not used	Fan, A/C	Fan, A/C	Fridge, misc. load	Not used	Not used
7 AM to 9 AM	2 lights, 2 fans, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Not used	Not used
9 AM to 12 PM	Not used	Light, fan, laptop	Not used	Fridge, misc. load, light, fan	Used	Not used
12 PM to 3 PM	Not used	Light, fan, laptop, A/C	Not used	Fridge, misc. load, light, fan	Used	Not used
3 PM to 5 PM	Not used	Light, fan, laptop	Not used	Fridge, misc. load, light, fan	Not used	Not used
5 PM to 9 PM	2 lights, 2 fans, TV, A/C	Not used	Not used	Fridge, misc. load, light, fan	Not used	Charging
9 PM to 12 AM	Not used	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load	Not used	Not used

Table 5. Saturday (load usage, 5PM to 12PM house is empty)

Time	Living Room	Bedroom 1	Bedroom 2	Kitchen	PV	EV
12 AM to 9 AM	Not used	Fan, A/C	Fan, A/C	Fridge, misc. load	Not used	Not used
9 AM to 10 AM	Light, fan, TV	Not used	Not used	Fridge, misc. load, light, fan	Used	Charging
10 AM to 12 PM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Used	Charging
12 PM to 1 PM	Light, fan, TV	Light, fan, laptop, A/C	Light, fan, laptop, A/C	Fridge, misc. load, light, fan	Used	Charging
1 PM to 3 PM	Light, fan, TV	Light, fan, laptop, A/C	Light, fan, laptop, A/C	Fridge, misc. load, light, fan	Used	Not used

3 PM to 5 PM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Not used	Not used
5 PM to 12 AM	Not used	Not used	Not used	Not used	Not used	Not used

Table 6. Sunday (load usage)

Time	**Living Room**	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**PV**	**EV**
12 AM to 9 AM	Not used	Fan, A/C	Fan, A/C	Fridge, misc. load	Not used	Not used
9 AM to 10 AM	Light, fan, TV	Not used	Not used	Fridge, misc. load, light, fan	Used	Not used
10 AM to 12 PM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Used	Not used
12 PM to 3 PM	Light, fan, TV	Light, fan, laptop, A/C	Light, fan, laptop, A/C	Fridge, misc. load, light, fan	Used	Not used
3 PM to 5 PM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Not used	Not used
5 PM to 9 PM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Not used	Charging
9 PM to 12 AM	Light, fan, TV	Light, fan, laptop	Light, fan, laptop	Fridge, misc. load, light, fan	Not used	Not used

B. Steady State Loss Analysis

Breakdown of energy losses in the DC nanogrid: In the DC nanogrid the total loss in the system was calculated using the following equation:

Total loss in DC nanogrid = Total line loss + Total device loss + Converter and conversion losses

Figure 18 shows the breakdown of energy loss in the DC nanogrid for all three cases.

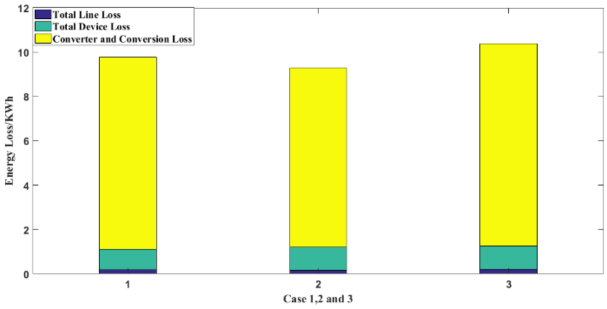

Figure 18. Breakdown of losses in the DC nanogrid for all three cases

Distribution line losses at the 380V DC bus vs 48 V DC bus: As mentioned earlier two cases are considered for power distribution in the DC nanogrid. Figure 19 shows the results for distribution line losses using 380V DC bus vs 48V DC bus for all three cases. It is clear from the results that distribution at 380V has less energy loss as compared to distribution at 48V. This is expected as $P=V * I$ indicates that at a higher voltage the energy loss decreases. But in the nanogrid 48V is selected for power distribution the reason being safety and commercial availability of domestic appliances at 48V. Although 380V bus provides less energy loss such a high voltage poses a great safety risk [25]. Moreover, as commercially available devices were selected for the simulation none of them were available at 380V, therefore 48V is selected for distribution within the DC nanogrid.

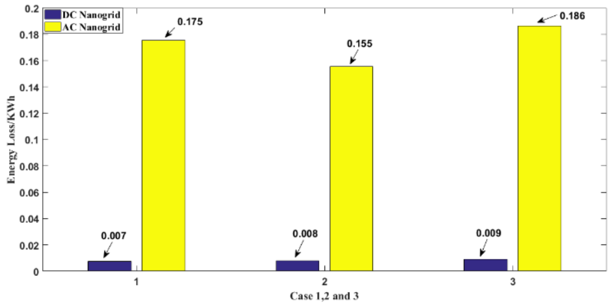

Figure 19. Distribution line losses using 480 V DC bus vs 48 V DC bus for all three cases

Breakdown of energy losses in the AC nanogrid; Figure 20 shows the breakdown of energy losses in the AC nanogrid for all three cases. The energy loss for the AC nanogrid is calculated using the following relationship

Total energy loss = Total line loss + Total device loss + Converter and conversion losses + Reactive power loss

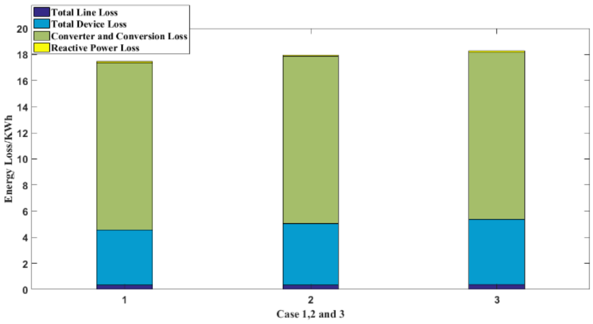

Figure 20. Breakdown of losses in the AC nanogrid for all three cases

Comparison of line losses between the DC and AC nanogrid: Figure 21 shows the comparison of line losses between the DC and AC nanogrid. It is evident from the bar graph that there are fewer line losses in the DC nanogrid as compared to the AC nanogrid. The reason for this is more efficient DC appliances in the DC nanogrid which require less current as compared to their AC counterparts. This reduction in current thus causes fewer line losses in the DC nanogrid. Furthermore, AC network has an additional reactive power loss in distribution which is not present in the DC nanogrid.

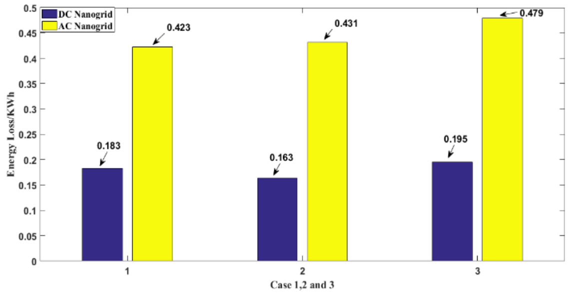

Figure 21. Total line losses in the DC nanogrid vs AC nanogrid for all three cases

<u>Comparison of device losses between the DC and AC nanogrid:</u> Figure 22 shows a comparison between device losses in the DC and AC nanogrids. The results indicate that device losses in a DC nanogrid are fewer. This is because DC appliances are more energy efficient and there are no conversion losses in the devices in the DC nanogrid [3]. A brushless DC motor used for modelling DC motor loads in the DC nanogrid is approximately 95% efficient [26], [27], [28] whereas the split phase induction motor used for modelling AC loads in the AC network has around 87% efficiency [29], [30]. Therefore, for loss calculation, 5% loss was considered for the brushless DC motor and 13% loss was considered for the split phase induction motor as dictated by their respective efficiencies. Moreover, AC-DC conversion in DC devices (Laptop, LED light, LED TV) present in the AC network was considered 95% efficient [31] with a 5% loss. This is an additional loss in the AC nanogrid. Due to these respective efficiencies and no conversion losses (AC to DC) in DC devices present in the DC nanogrid, there are fewer device losses in the DC network as compared to the AC.

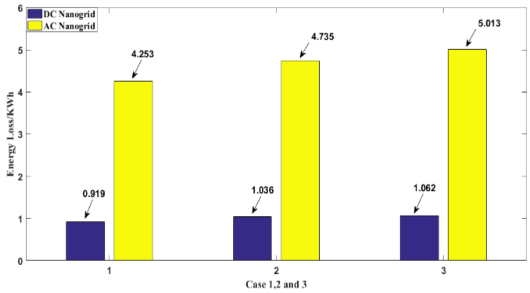

Figure 22. Total device losses in the DC nanogrid vs AC nanogrid for all three cases

<u>Comparison of converter and conversion losses between the DC and AC nanogrid:</u> Figure 23 shows the comparison between total converter and conversion losses in the DC and AC nanogrid. The converter and conversion losses in the DC nanogrid are comprised of

1. AC to DC conversion from the grid
2. DC to DC conversion from MPPT
3. DC to DC conversion for EV charging
4. DC to DC conversion between the 380V and 48V Bus.

In the AC nanogrid, the converter and conversion losses included

1. DC to DC conversion from MPPT
2. DC to AC conversion of solar output into the 230V AC Bus
3. AC to DC conversion for EV
4. DC to DC conversion for EV charging.

Using efficiency curves [32] the efficiency of AC to DC or DC to AC (Grid-tied inverter) conversion is considered as 92% with an 8% loss whereas DC to DC conversion is considered as 95% efficient with a 5% loss. It is clear from the figure that converter and conversion losses are less in the DC network the reason being the respective efficiency of AC to DC and DC to DC conversions and fewer AC to DC or DC to AC conversions in the DC nanogrid.

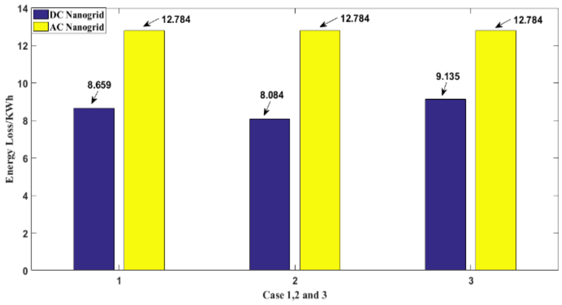

Figure 23. Total converter and conversion losses in the DC nanogrid vs AC nanogrid for all three cases

<u>Comparison of total losses between the DC and AC nanogrid:</u> The total losses in both DC and AC NG are the sum of all the losses mentioned in Figure 18 and 20. Figure 24 shows the cumulative losses in a DC and AC nanogrid. As line losses, device losses and conversion losses are less in the DC nanogrid, the total system losses in the DC

nanogrid are fewer as compared to the AC nanogrid as shown by the bar graph. This shows that a DC nanogrid is better than an AC nanogrid when compared based on energy efficiency [33].

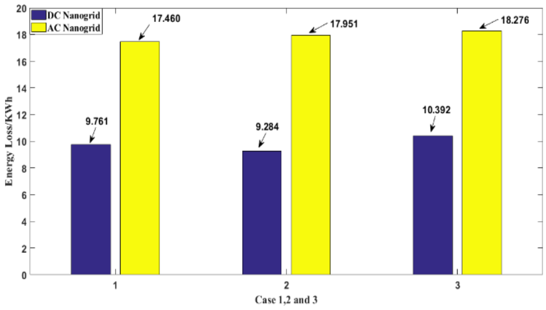

Figure 24. Total system losses in the DC nanogrid vs AC nanogrid for all three cases

Comparison of power drawn from the grid between the DC and AC nanogrid: Figure 25 shows the total power drawn from the grid for both DC and AC nanogrid. The plot clearly shows that in a DC nanogrid less power is drawn due to the high efficiency of the network.

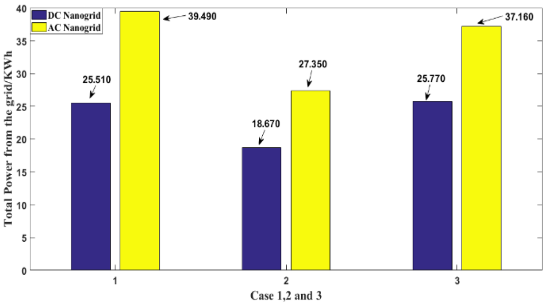

Figure 25. Total power from the grid in the DC nanogrid vs AC nanogrid for all three cases

Another advantage of a DC nanogrid is less energy usage from the grid which consequently leads to fewer electric bills. Net power was calculated for both networks using the following relationship: Figure 26 clearly shows that net power drawn in a DC nanogrid is less as compared to the AC nanogrid. This is because of high system efficiency in a DC nanogrid and availability of efficient DC devices which provide the same features at less wattage as compared to the AC devices. Therefore, energy losses are reduced in the DC nanogrid, and less power is drawn from the grid. This has immense importance for the consumers as less power from the grid means that a DC nanogrid user will have to pay fewer amount of electric bill as compared to an AC nanogrid user.

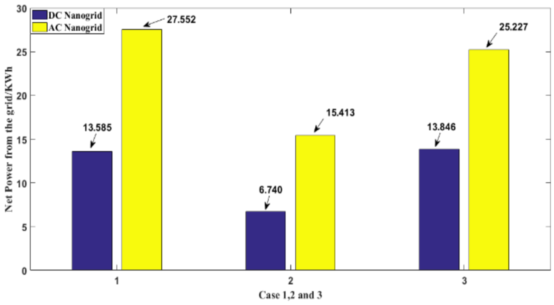

Figure 26. Net power = (Total power from grid – Power form PV) from the grid in the DC nanogrid vs AC nanogrid for all three cases

C. *Economic Analysis*

An economic analysis was performed between the DC and AC loads i.e., air conditioner, fan, and refrigerator. The other DC loads were excluded as those are common in both the DC and AC network. It is clear from the loss analysis that in terms of efficiency DC devices are better, this analysis is performed to determine how those energy savings affect the payback period and if it is feasible to use DC devices since their upfront cost is higher as compared to AC devices. The table below shows the cost of DC and AC devices used in both networks. For both the DC and AC air conditioners the price for 12000 BTU/h model is used as the price for15000 BTU/h model is not available. Table 7 shows the cost details.

Table 7. Cost of DC and AC devices [23], [34], [35], [36], [37], [38]

	DC fan	AC fan	DC refrigerator	AC refrigerator	DC A/C	AC A/C
Cost (PKR)	15,593	13,907	31,608	25,000	1,58,040	1,42,130
Total cost = (No. of device * cost) (PKR)	77,965	69.535	31,608	25,000	4,74,120	4,26,390

The total cost of DC devices = 5,83,423 PKR
The total cost of AC devices = 5,20,925 PKR

Figure 27 shows that the upfront cost of DC devices is more as compared to AC devices.

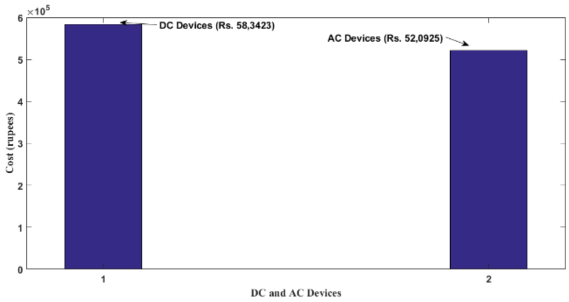

Figure 27. Cost of DC vs AC devices

So, the extra cost of DC devices = 5,83,423 – 5,20,925 = 62,498 PKR. Considering an average unit price of 13 PKR [39] the total energy bills per month for the DC and AC nanogrid can be computed as follows.

Units used in a month in the DC nanogrid = 354.0 KWh, units used in a month in the AC nanogrid = 713.6 KWh. Therefore, the monthly bill for a user in DC nanogrid = 354*13 = 4,602 PKR whereas, the monthly bill for a user in AC nanogrid = 713.6*13 = 9,277 PKR. Figure 28 shows these results that the electric bill for DC devices is less as compared to the AC devices.

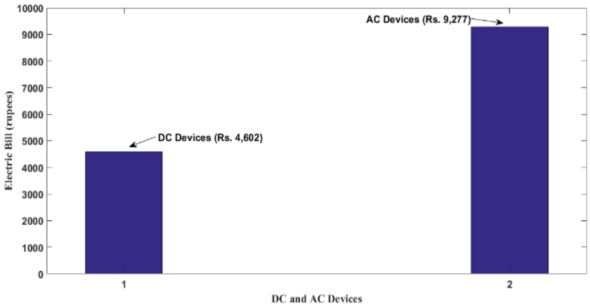

Figure 28. Monthly bill of DC vs AC devices

Moreover, the monthly savings using a DC nanogrid = 9,277 - 4,602 = 4,675 PKR. The payback period for the extra cost of DC device = 62,498 / 4,675 = 13.4 (13 and a half months).

According to this economic analysis although the upfront cost of DC devices is more than the AC devices due to the higher efficiency of DC devices, the electric bill is also reduced. The extra amount paid for the DC devices can be recovered approximately in thirteen and a half months because of the reduced electric bills.

CONCULSION

There is a huge debate at present between the use of AC and DC systems. This paper makes a comparison between a DC and AC nanogrid based on system losses to determine which network is more efficient. A DC and AC nanogrid network are modelled in MATLAB/Simulink with main components including a PV array, grid-tied inverter, electric vehicle, and various domestic loads developed based on commercially available products. Case studies are then created to measure the system losses in both networks. The results clearly indicate that losses in a DC nanogrid are fewer as compared to an AC nanogrid. The reason for this is more efficient DC devices and their increased accessibility, fewer power conversions in a DC system and availability of DC power (PV) and storage (EV) sources. Furthermore, the analysis also shows that a DC nanogrid user draws less energy from the grid because of fewer losses and more efficient devices. This results in fewer electric bills and more economic benefit to a DC nanogrid user. Although the cost of DC devices is more than the AC devices according to the economic analysis performed in this study the savings due to reduced electric bills in a DC nanogrid can recover the extra cost within a period of 14 months. Thus, this study shows that a DC nanogrid is better in terms of energy efficiency than an AC nanogrid and offers economic benefit to the user and therefore should be preferred in places where efficiency is a top priority.

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