

Energy Savings Using Direct Current (DC) from Photovoltaic (PV) System in a Residential Home

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Abstract - The conventional AC nanogrid with photovoltaic (PV) system has suffered from power loss caused by power conversion from DC to AC and back to DC for most of the end use in a typical residential home. To overcome the problem, DC nanogrid is proposed in this paper. Partial and full DC nanogrids are designed and their efficiencies are compared with a full AC nanogrid. The simulation study results show that partial DC nanogrid has 79.2% of overall efficiency while AC nanogrid has 71.87%. Furthermore, the efficiency is improved to 99.74% for a full DC nanogrid. It proves the less amount of power conditioners used in the system the higher the efficiency can be obtained. Moreover, an economic evaluation is conducted on the proposed two DC nanogrids to investigate whether they are sustainable and feasible. From the simulation studies conducted, it is shown that partial DC nanogrid saves electricity bill and capital cost but full DC nanogrid is not feasible even if it saves electricity bill spectacularly high but it needs extremely expensive capital cost.

Keywords - Nanogrid, PV, AC, DC

I. INTRODUCTION

Alternating current (AC) power distribution system has dominated long distance power distribution for almost a century [1].

Microgrid is considered as a single controllable system [2]. It controls both generation and load sides to satisfy electricity demand, auxiliary service or feed power back to utility grid. Point of common coupling (PCC) is required for both network to adjust power level from the grid. It is obvious that power conversion employed in direct current (DC) is less than AC by eliminating rectifiers and replacing them to converter. However, most of household appliances are DC-based load which loaded by AC-DC rectifier [3]. Rooftop photovoltaic (PV) source and energy storage system such as battery are DC-based, which makes DC conversion easier and more efficient. Energy saving is generally is high which can go up to 20% with the help of DC microgrid/nanogrid [2]. Moreover, high penetration of DC appliances in the market and technology advances have improved efficiency of DC regulation and AC-DC rectifiers [1, 4]. Therefore, DC power distribution system (DC microgrid/nanogrid) has potential to improve energy savings as compare to conventional AC network [1].

Many researchers focused on DC microgrid/nanogrid

for commercial buildings especially for lighting devices [5]. Less effort was put on residential appliances. Few researchers investigated DC PV microgrid/nanogrid for residential in US and Denmark [5, 6]. However, the above mentioned authors concentrated on safety and electricity bill and hence introduce the concept of low voltage DC. Reference [7] analyzed the power converters used in both microgrids/nanogrids and pointed out quantity of that in DC line is less than AC. When DC generation is applied to microgrids/nanogrids, efficiency of semiconductors gets improved by half and current ripple is less in DC microgrids/nanogrids. Reference [8] conducted an overall study on AC and DC microgrid/nanogrid powered by renewable energy system. The authors pointed out that micro-converter used in AC system occurs inefficient effect to power distribution. Operation of low voltage AC and DC was compared. They suggested that DC microgrid/nanogrid was the main power system in the future due to raising quantity of DC-based devices in residential and business. Reference [9] carried out a case study including 1MW PV system. It was shown that DC microgrid/nanogrid performed as the worst structure among all other aspects which are economical operation, reliability and annual cost. This is caused by relatively low efficiency of DC/DC converter used in DC microgrid/nanogrid. This finding contradicts the studies done by most of other researchers. Reference [10] analyzed the economic advantage of DC distribution of lighting system in commercial building in US. The authors focused on lighting instead of all other appliances in the building due to central lighting supply which has most potential. The authors found out by applying grid-connected PV based distribution system, unsubsidized capital cost and levelized annual cost of lighting a few decreased up to 21%. The DC PV based distribution is much more economical as compared to the AC distribution.

In this paper, a DC nanogrid from PV system in residential is proposed. A DC and an AC nanogrid configurations are designed and simulated via Matlab Simulink. The studies were based on a typical residential home in Auckland, New Zealand. Equivalent of common electrical appliances are considered. Furthermore, both low voltage and high voltage appliances are included. Technical evaluation and economic evaluation are conducted to both DC and AC nanogrids. Finally, an overall investigation on DC nanogrid for PV system versus AC nanogrid is performed. The innovation of this research is to find out whether DC

nanogrid has higher efficiency and economic value. Since solar radiation of Auckland, New Zealand is low, there is no research has ever made to prove if DC nanogrid built for New Zealand household is practical. The proposed system is designed in the way that split DC and AC loads and supply them separately so that the quantity of power conditioners is optimum. Since control strategy of nanogrid is not the major aim of this research, the standard control method is utilized in the study.

II. METHODOLOGY

A. AC Nanogrid

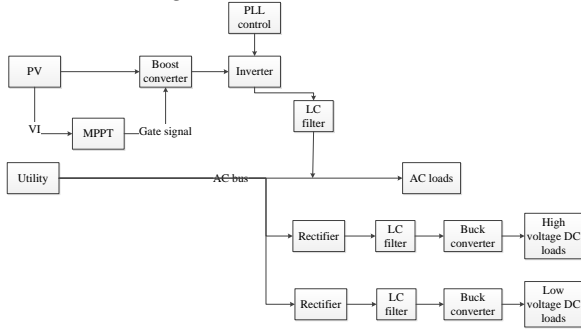


Fig. 1 Overall AC nanogrid configuration

Fig. 1 shows the completed single phase 50Hz, 230V RMS AC nanogrid system design. Power generation station and transformer are not included in this design. Irradiation and temperature are the inputs of PV array. For Auckland, the average annual irradiation and temperature are 175.83W/m^2 and 16.1°C respectively. A perturb and observe (P&O) maximum power point tracking (MPPT) is utilized. It perturbs the output voltage of PV array and calculates the corresponding power at that condition. The calculated power gets compared with current power in order to update the maximum power value. If the new calculated power is higher, it will update current power by replacing the calculated one. Otherwise, it will maintain the previous power value. Power transmission and wire loss due to it are not considered in this study. A Phase Lock Loop (PLL) is used in the system to ensure that the output of inverter is an AC voltage that synchronizes the AC voltage generated by utility. Hence, the frequency and phase of inverted voltage from solar array are locking into frequency and phase of utility. Since both are constant, the changing of frequency and phase are not considered in this situation. An AC bus is used to connect power supply and loads. Rectifiers are required to convert AC voltage to DC for DC loads. Both high voltage and low voltage DC loads are connected to AC bus via diode based two arms rectifier. Since voltage applied on AC bus is 230V RMS, peak voltage is 325V. Hence, the line voltage which gets converted to DC is nearly equal to 325V. Therefore, a step down DC-DC buck converter is required to adjust line voltage to 230V and 20V respectively.

B. Partial DC Nanogrid

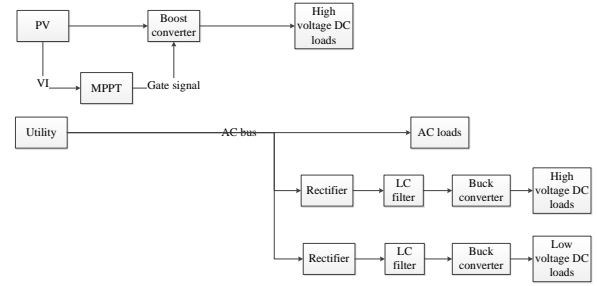


Fig. 2 Overall partial DC nanogrid configuration

Fig. 2 shows the configuration of proposed partial DC nanogrid. The idea of replacing AC nanogrid by DC is based on the implementation of electricity distribution in DC form because it requires less amount of power conditioners used to convert AC to DC. The other benefit of using DC nanogrid is that phase lock and synchronization are not required to be considered. The idea of this design is utilizing the PV array to supply some of DC loads individually so that some part of the loads does not require rectifier to convert AC to DC and hence reduce the conversion losses. It is assumed that maximum capacity of the installed PV is 2 kW and thus, only 2kW high voltage DC loads are supplied by PV array. The rest of loads are supplied by utility. Due to the system only supplies some of DC loads, it is called partial in this paper. Since PV is not connected to AC bus, the system is much simpler, and loss of energy is much less than AC nanogrid theoretically.

C. Full DC Nanogrid

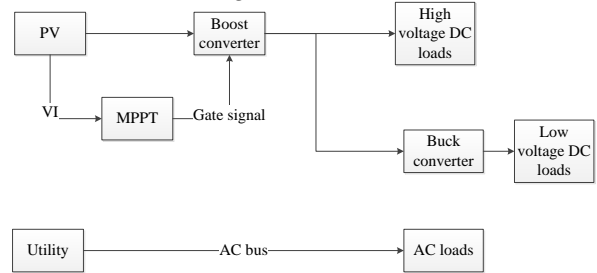


Fig. 3. Overall full DC nanogrid configuration

Fig. 3 shows the whole system of full DC nanogrid. Total consumption of DC loads is 9674W. Hence, the size of PV array is enlarged. The high voltage DC can be connected to PV array directly, but low voltage DC loads require buck converter to be supplied by the PV. The rest of loads are AC loads only, hence, they are supplied by utility directly. Since this arrangement is AC source feeds AC loads, power conversion and phase synchronization are not included. Thus, power loss in this part is zero theoretically. It can be seen that DC and AC loads are divided and supplied by DC and AC source respectively. The only power conditioners used are the boost converter for PV array and buck converter for low voltage DC loads. Hence, efficiency of this design is much higher than the previous two systems. The line losses are not considered in this research because it is not significant since there is

no long wire (residential home). The design shown in this paper is a very ideal design, which is used to prove the point that the less amount of power electronics use in the system, the less power loss is caused by power distribution. In another word, separating different loads to be supplied by different power supply achieves highest efficiency and hence the goal of energy saving is achieved.

III. RESULTS

To test power efficiency of all three systems, simulation and calculation of power for source and loads are carried out using MATLAB in this Section.

For the AC nanogrid, power sources are coming from PV and utility. The power of PV array is calculated by output voltage multiply by output current. Both are measured automatically by measurement ports of PV array set in MATLAB. By amplifying them, the result is shown below.

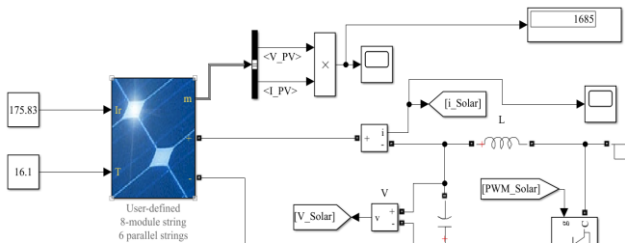


Fig. 4 PV array output power in AC nanogrid

Fig. 4 shows the output power of PV array is 1685W. For the utility, power is calculated by multiplying RMS value of voltage and current.

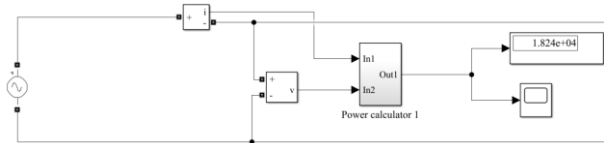


Fig. 5 Utility output power in AC nanogrid

Fig. 5 shows the output power of utility is 18.24kW. AC loads, high voltage DC loads and low voltage DC loads are the main elements that consume the power calculated. For AC loads, power consumption is calculated by using RMS value of input voltage and current. The power consumption of all loads in AC nanogrid where AC loads took 4693W, high voltage DC loads took 9486W and low voltage DC loads took 140.5W. To calculate overall efficiency of AC nanogrid, the sum power consumption for all loads and divided by the sum of output power from both power source. The overall efficiency for AC nanogrid is 71.87%.

For the partial DC nanogrid, PV array and utility are still the power sources of the system. Loads are divided into two parts including AC loads, low voltage DC loads, high voltage loads supplied by utility and PV array.

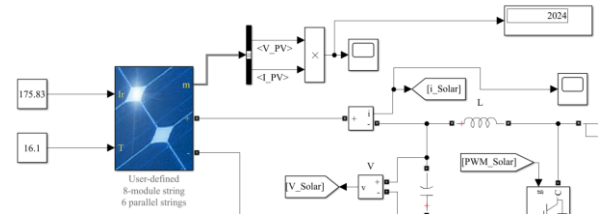


Fig. 6 PV array output power in partial DC nanogrid

Fig. 6 shows output power of PV array is 2024W. These amount of power is fed to high voltage DC loads which supplied by the PV array only.

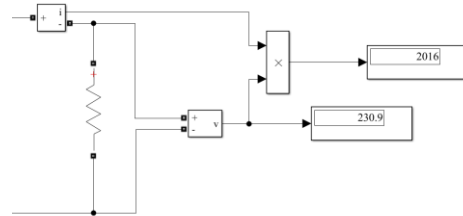


Fig. 7 Power consumption of DC loads supplied by PV array in partial DC nanogrid

Fig. 7 shows power consumption of DC loads supplied by PV array only and the value is 2016W. Thus, there is a loss of 6 W which is very insignificant.

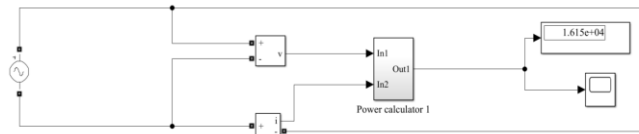


Fig. 8 Utility output power in partial DC nanogrid

Fig. 8 shows power generated by utility in partial DC nanogrid is 16.15kW. The power consumption of all loads in partial DC nanogrid where AC loads took 4693W, high voltage DC loads took 7540W and low voltage DC loads took 140.5W. To calculate overall efficiency of partial DC nanogrid, the sum power consumption for all loads and divided by the sum of output power from both power source. The overall efficiency for partial DC nanogrid is 79.2%.

For the full DC nanogrid, all DC loads no matter high voltage or low voltage are supplied by the PV array only. To supply all DC loads, PV array needs to be up-sized in term of capacity so that its output power is sufficient for those loads. Power sources in this system are still PV array and utility. Loads considered in this system are AC loads, low voltage DC loads and high voltage DC loads.

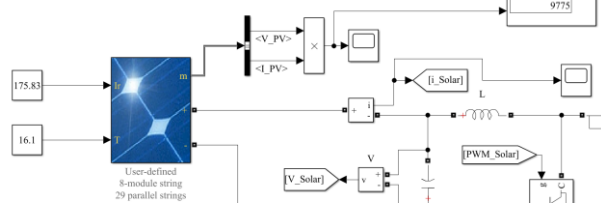


Fig. 9 PV array output power in full DC nanogrid

Fig. 9 shows the power produced by PV array is 9775W. This amount of power is delivered to all of the DC loads. The power consumption of all DC loads in full DC nanogrid where high voltage DC loads took 9595W and low voltage DC loads took 142.8W.

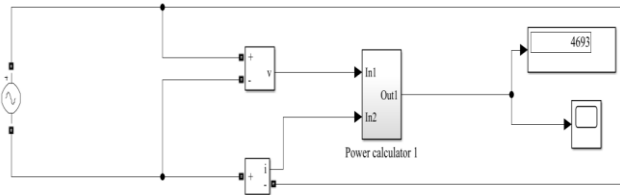


Fig. 10 Utility output power in full DC nanogrid

Fig. 10 shows output power of utility. For AC loads, it is directly fed by utility. The power consumed by AC loads is 4693W. Hence, total efficiency can be calculated by the sum power consumption of all loads and divided by sum of power supplied by both power source. The total efficiency of full DC nanogrid is 99.74%.

IV. DISCUSSIONS

From the previous Section, it is obvious that the efficiency of full DC nanogrid is the highest among the other two configuration e.q. partial DC nanogrid and AC nanogrid. It is very obvious that the AC nanogrid is obtained as lowest efficiency system since there are number of power conditioners are used. In the partial DC nanogrid, there are 1 boost converter, 2 rectifiers and 2 buck converters. Out of 2024W that generated by PV array, 2016W gets utilized by the loads, which means the loss on boost converter is 0.39% by neglecting wire loss. Out of 16.15kW generated by utility, 12.3735kW is delivered to loads, which means power loss on rectifiers and buck converter is 23.38%. Power generated by PV array takes 11.14% of total power generation in this system.

In the full DC nanogrid, there are only 1 boost converter and 1 buck converter. Power generated is 100% delivered to the loads since there is no wire loss. Out of 9775W supplied by PV array, 9737.8W is used by loads, which means power wasted on the buck converter and boost converter is 0.38%. Utility is directly connected to AC loads so that the power is 100% used since wire loss is ignored. Hence, power loss that caused by buck converter and boost converter is very little which can be ignored. It can be said that using of rectifiers is the major reason for power loss in the DC system. Power generated by PV array takes 67.56% of total power generation in this system.

In the AC nanogrid, power electronics used are 1 boost converter, 1 inverter, 2 rectifiers and 2 buck converters. To obtain power delivered to AC bus by PV array, a power conditioner is added to output side of inverter designed for PV array.

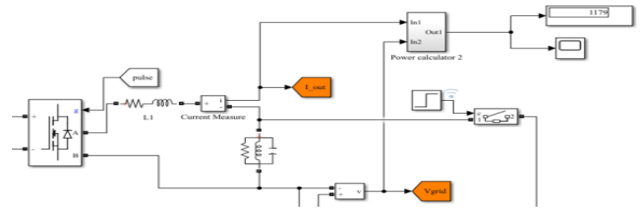


Fig. 11 Power delivered to AC bus by PV array

Fig. 11 shows out of 1685W generated by PV array, only 1179W is delivered to AC bus, which means power loss by boost converter and inverter is 30%. As mentioned earlier, the amount of power loss on boost converter is very small, power loss is primarily caused by using inverter. Out of 1.179kW + 18.24kW=19.419kW supplied by utility and PV array, 14.3195kW is used by loads, which means power loss on rectifiers and buck converters is 26.26%. The overall power loss is 28.13%. Power generated by PV array takes 8.46% of total power generation in this system. From all the results shown, it can be concluded that buck converter and boost converter do not consume much power while working. However, rectifier and inverter take the major responsibility for power loss. From the simulation studies conducted, rectifiers cause 23%-26% power loss and inverter causes 30% power loss. The simulation studies results prove that power conditioners are one of the major reasons for getting higher losses and thus lower efficiency. The proposed DC microgrid/nanogrid eliminates most of power conditioners, hence, it will reduce losses and thus it achieves highest efficiency among all other systems.

Economic evaluation is carried out in this Section as well. Prices of electricity are taken from one of utility retailers in Auckland and they are as follows: fixed price is 61.65c/day and uncontrolled charge is 18.58c/kWh. Electricity consumption is taken from a typical household which receives electricity charge on July 2018. It consumes 98.7kWh and the total bill excludes Good and Services Tax (GST) is NZ\$37.45. In this research, discount on electricity charge issued by utilities and goods and service tax (GST) are not considered because both values are case by case basis.

For AC nanogrid, its efficiency is 71.87%, hence, it requires 137.33kWh power supply. Among this consumption, 8.46% is supplied by PV array so that power generated by utility is 125.71kWh. The electricity bill is NZ\$42.47 and it is calculated based on the followings:

$$125.71\text{kWh} * \$0.1815/\text{kWh} + \$19.11\$ = \$42.47.$$

For partial DC nanogrid, its efficiency is 79.2% so that power supply requirement is 124.62kWh. There are 11.14% generated by PV array so that 110.74kWh is supplied by the utility. Hence, electricity charge is NZ\$39.21.

For full DC nanogrid, its efficiency is 99.74% so that the power supply requirement is 98.96kWh. Out of this amount of power, 67.56% is supplied by PV array so that

32.1kWh is generated by utility. Electricity charge is NZ\$24.94.

To build the AC nanogrid, several elements need to be purchased such as PV array, inverter, rectifiers and converters. A typical 2kW PV array with inverter costs around NZ\$5,180. Rectifiers used for both DC loads cost NZ\$27.4 each. Converter used for both DC loads costs NZ\$14.94 each. Capital cost of building AC nanogrid is NZ\$5,268.68. The price of cables and switches are neglected because for all systems those elements are required. The price of those equipment does not make much difference between three systems.

For partial DC nanogrid, elements used in the system includes PV array, rectifiers and converters. A 2kW PV array without inverter costs NZ\$4,479.07 is used. Rectifiers used for both DC loads cost NZ\$27.4 each. Converter used for both DC loads costs NZ\$14.94 each. Capital cost of building partial DC nanogrid is NZ\$4,563.75.

For full DC nanogrid, there is only one buck converter used for low voltage DC loads and the price is NZ\$14.94. However, the size of PV array is five times larger than the one used in the partial DC. Hence, the cost of PV array is NZ\$22,395.35. Capital cost of building the full DC is NZ\$22,410.29.

From the cost estimation presented above, it can be seen that the partial DC nanogrid saves electricity bill roughly NZ\$3.26 per month as compared to the AC nanogrid. The capital cost of the partial DC nanogrid is NZ\$704.93 less than it of the AC nanogrid. Normally, warranty of PV array is 25 years, which means using partial DC nanogrid can save about NZ\$1,682.93 as compared to the AC nanogrid. For the full DC nanogrid, it saves electricity bill by NZ\$17.53 roughly per month. However, the capital cost of full DC nanogrid is extremely high. It costs NZ\$17,141.61 more than the AC nanogrid does. In 25 years, the full DC nanogrid is able to save electricity bill by NZ\$10,518 roughly but it is still not able to pay back the capital cost.

V. CONCLUSION

In this research, two DC nanogrids are designed and simulated based on PV array and grid-tie connection. The first DC nanogrid is designed in the way that it supplies some DC loads using PV array directly so that usage of inverter is skipped. Power efficiency is improved to 79.2% as compared to the AC nanogrid (71.82%). The improvement is 7% and hence electricity bill is decreased by NZ\$3.26 roughly per month.

In AC nanogrid, power losses due to inverter is 30%. That explains the reason why AC nanogrid has lowest efficiency. Efficiency reduced by rectifier and converter is between 23%-26%, which is not dealt with in the proposed partial DC nanogrid. Hence, the efficiency gets improved is limited. The third study system called full DC nanogrid is designed. All DC loads are supplied by PV array and hence inverter and rectifiers are not required in

the system. AC loads are supplied by utility only. Therefore, power loss on AC loads is neglected. However, even if full DC nanogrid boosts efficiency up to 99.74% and reduces electricity bill by NZ\$17.53 roughly per month but it is extremely expensive. However, designing and simulating of the full DC nanogrid is still meaningful because it proves the point that less amount of power conditioners used in the system the higher efficiency is obtained. In this research, power loss caused by transmission and wires are not considered, which makes the system potentially to be improved. It is assumed that all the loads are the same so that power level and constrains of different loads are not considered in this research. Otherwise, these facts will change the study results. Hence, for the future research, it is suggested to consider load levels and constrains of appliances in order to further improve the system.

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