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Integration of DC Households System Generated by Single-Phase Rooftop PVs into Unbalanced Three-Phase Residential Feeder

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Abstract

This paper mitigates the integration of DC households that generated by single-phase photovoltaic (PV) into the unbalanced three-phase residential feeder. As solar energy has been noticed producing DC power, then it would be reliable to put the households loads into usable DC. The integration of grid-connected single-phase rooftop PVs into the DC distribution system would involve fewer components, which eventually reduce the cost of the system. The proposed design of the DC distribution system consists of single-phase rooftop PV with the rating of 1-5kW, DC-DC converter as the most important device to interface with the grid and battery storage, and also the rectifier for DC operated appliances and last but not least, households' DC usable loads. As the design simulated in Matlab platform, the results indicate that at day times, as PV penetrated over than 50%, it reduced the imbalanced impact of the three-phase feeder, thus voltage profile still within its standard limit. Rectifiers also improved its efficiency. The households' appliances were divided into high power 380V and low power 24Vand categorized as non-controllable, permanent, programmable, and rechargeable loads presented their efficiency and the energy consumption within 24 hours. The DC households successfully improved the consumption of electric energy.

Keywords: DC households, rooftop PV, DC-DC converter, battery storage, unbalanced three-phase feeder

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1. INTRODUCTION

As the trend of renewable energy sources increasing, the implementation of distributed generator (DG) such as photovoltaic (PV), wind turbine, thermal power, etc., either grid-connected or stand-alone tends to take into account. Recently, direct current (DC) power is increasing its amount in the generation side as PV generated DC power. It means that solar energy has being noticed producing DC output as well. Several studies of DC distribution systems have only been focused in data centres and commercial buildings [1-4]. While the settlements for DC distribution commercial buildings have shown to be advantageous, however, less focus has been put into residential DC distribution. Residential households would require a different approach compared to commercial buildings and renewable energy generation is less likely to be utilized in the residential segment [4,5]. By using DC for distribution systems it would be possible to savings and higher reliability due to a decreased number of components. Moreover, energy delivery at DC is characterized by lower losses and voltage drops in lines [5].

Mostly residential households are supplied with 220-240V AC. To convert the AC voltage to usable DC, it is requiring rectifiers for DC operated appliances. In DC distribution systems, DC-DC converter is the most important device to interface with the grid and battery storage. Considering the consumer side, modern households appliances such as laptops, mobiles, LED lighting, television, microwave oven, etc., have to be DC operated appliances. DC power also needs to be implemented in households, or modified into existing ones, with minimal impact to the appliances. This paper is proposing a DC distribution system for residential households, which have DC loads and powered by single-phase rooftop PVs. The integration of grid-connected single-phase rooftop PVs into the DC distribution system would involve fewer components, which eventually reduce the cost of the system. The rest of the paper is organized as follow; section two discussed the literature review of DC distribution systems, single-phase rooftop PV, and DC loads. In section three, the proposed approach is detailed, as the design and the simulation of developed system. Several case studies are developed and the results are discussed in section four. Finally, section five is concluding the entire sections of the paper.

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2. LITERATURE REVIEW

This section is briefly discussed several studies that have been conducted regarding DC distribution systems, the performance of single-phase rooftop PVs into the systems, and the advantages of DC households.

2.1. DC Distribution Systems

DC distribution offers a micro-grid that delivers DC voltage at two levels, 380V and 24V. Studies have been conducted in residential DC distribution that appear to encouraging a low voltage (LV) only solution of either 24V or 48V. These voltage ratings are able to power fewer number of electronic devices. However, several household appliances consider as high power electronics devices, such as centralized air conditioning, high-power microwaves, dryers, etc., then the 380V levels need to take into account. According to EMerge Alliance [2] it is stated that by introducing high voltage (HV) components, allows high power to be utilized in a DC-powered home. As LV level was chosen to be 24V requires specific insulation requirements, then HV level was chosen to be 380V for the micro-grid that has been developed as standard connectors, ports, and insulation requirements.

The possibility of implementing DC power for households appliances must apprehend the distribution design-related aspects such as the system architecture or its voltage level. Moreover, the unique challenges associated with DC power systems protection and stability had been mitigated in Elsayed et al., [4]. While another design of a 380V/24V DC micro-grid for residential DC distribution is discussed in Webb [6]. In addition, detail of the initial design of a DC house project was introduced in Crowfoot [7], as the design and model of the DC load had been simulated via Matlab/Simulink platform.

2.2. Single-phase Rooftop PVs

As mentioned in Safitri [8], currently, rooftops PVs are being installed depend on the attitude and financial circumstance of householders. Several benefits and drawbacks of PV system in the LV network can be seen briefly in Table 1.

Table 1
Benefits and drawbacks of PV [8]

Benefits of PV
PV systems provide green, renewable power by exploiting solar energy. It can be used as an alternative energy source in place of electricity generated from conventional fossil fuels.
PV panels constitute a reliable, industrially matured, green technology for the exploitation of solar energy. Several PVs' companies provide valuable warranties for PV panels in terms of both PV panel life span and PV efficiency levels across time. PV panels can last up to 25 years or more, some with a maximum efficiency loss of 18% only, even after 20 years of operation.
Unlike wind turbines, PV panels operate autonomous without any noise generation as they do not incorporate any moving mechanical parts. Furthermore, in adjustable PV systems, the movements are very moderate, almost negligible, and do not generate any disturbances.
With respect to operating and maintenance costs, PV panels do not require operating or maintenance costs.
PV panels can be ideal for distributed power generation as they are highly suitable for remote applications, such as in a remote farmhouse. By maintaining relatively small power generation stations in a distributed power network, it can minimize energy losses in the network that are caused by the long distance between power generation and power consumption points.
With respect to the fixed-tap distribution transformer for stepping down voltage from MV to LV, since the focus in this thesis is LV network (11kV/415V), then the transformers are universally fixed-tap.
Drawback of PVs
The biggest disadvantage of PV panels is their limited efficiency levels; compared to other renewable energy sources – such as solar thermal – PV systems have a relatively low efficiency level in the range of 12-20%.

The PV module comprises several PV cells joined together. This module absorbs the sunlight energy (photons) and converts it to voltage. The unidirectional flow of negative charge forms DC. To ensure a continuous supply of electrical energy, batteries have a large storage capacity in order to be used when solar radiation is minimal. The battery is connected directly to the DC bus of the grid-connected. It should have a high efficiency close to 100%. The maximum power point tracker (MPPT) technique is used to extract maximum power from solar panels and continuously deliver the highest power when load variations in irradiations and temperature occur. Although the MPPT will ensure smooth charge and discharge of the battery, this alone is insufficient to increase the battery life [9]. PV generator supplied a constant output depending on the solar radiation levels. Furthermore, the battery allowed excess energy to be stored and the battery output was used as backup power to restore system balance. It was also seen in the grid-connected mode that excess power supplied by the PV generator was supplied to the main grid. Finally, as the main grid has a higher priority than the diesel generator in providing backup energy, thus resulting in lower operation costs [9].

2.3. Advantages of DC Households

The DC household offers advantage by reducing the conversions between the micro-grid and battery backup. Alike to renewable generation, battery backups benefit from

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DC by disregarding the need to convert DC-AC and AC-DC. DC households implemented with battery backups only require DC-DC converter between the battery and micro-grid for charging and discharging. The DC household can also make use of home-to-grid, allowing for the household to generate power for the grid from the battery and renewable energy source with use of a bidirectional rectifier [6].

Savage et al., [10] sets forward an interesting discussion on the energy savings that could be achieved if appliances are changed to their DC alternative and unnecessary conversions are avoided. Figure 1 shows the potential of energy savings by shifting to DC appliances and avoiding AC-DC conversions for different appliances in a household on average, 14% on avoiding AC-DC conversions and 33% on shifting to the best DC alternative.

3. PROPOSED METHOD

This section is detailing the proposed of DC distribution system for households with single-phase rooftop PVs in three-phase residential feeder step by step. Firstly, it starts at the power source side, by modelling the single-phase rooftop PVs. Then continue to include the battery into the system. As DC loads is determined, then the configuration of a single DC household system is established. Finally, the integration of this configuration into unbalanced three-phase residential feeder is set to be simulated using Matlab platform.

3.1. Modelling of the rooftop PVs

Rooftop PVs can be modelling based on their injected active and reactive power. According to Figure 2, several calculations can take into account.

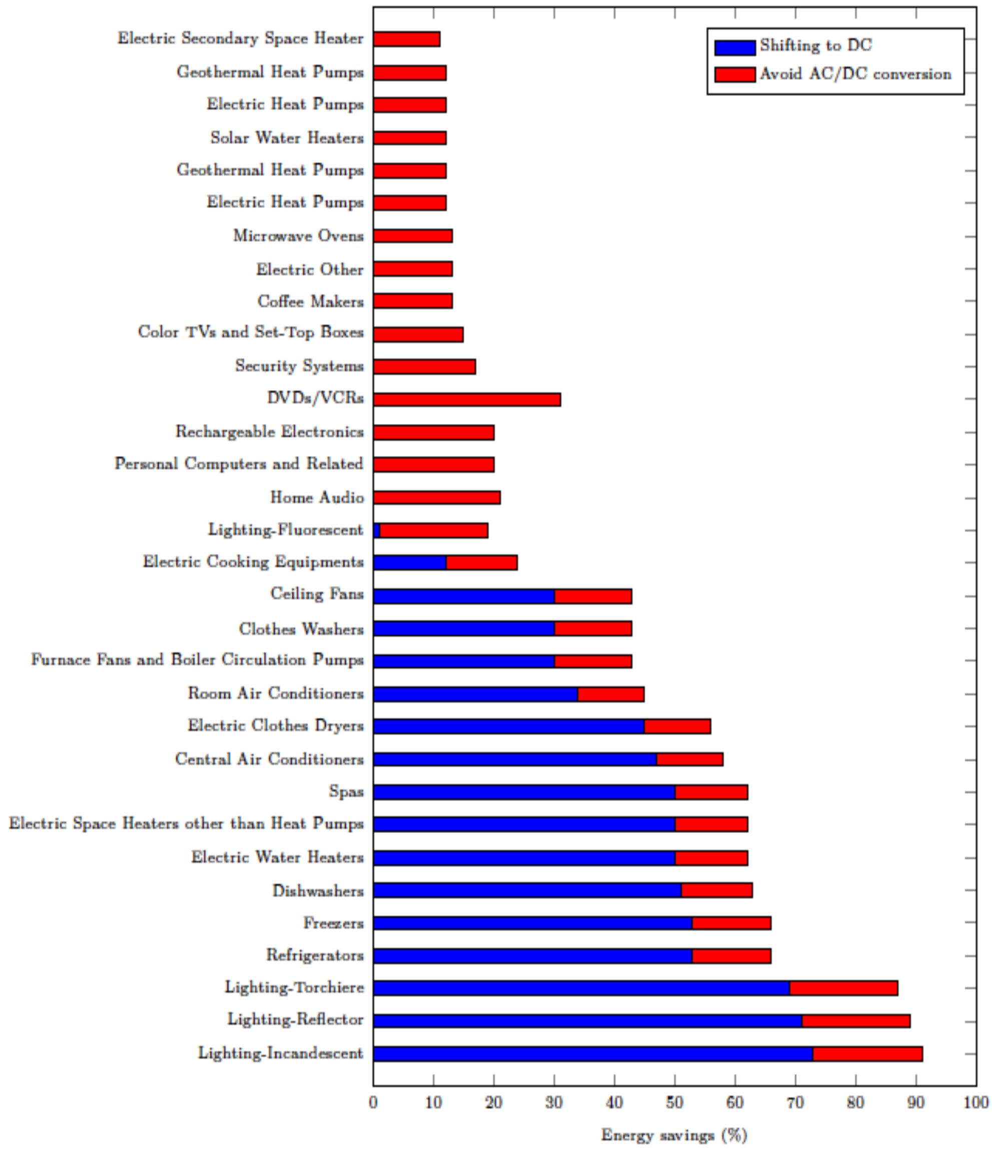

Figure 1. Potential of energy savings by shifting to DC appliances for different appliances in a household [11]

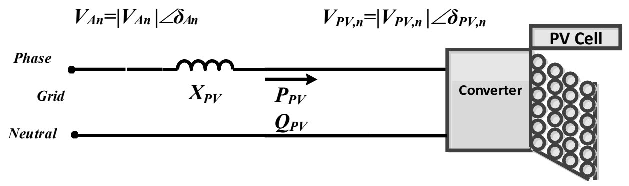

Figure 2. Detail diagram of single-phase rooftop PVs

The rooftop PV voltage magnitude and phase angle ($|V_{An}|$, δ_{An}) in Figure 1 can be computed based on its injected power $(\boldsymbol{P_{PV}}, \boldsymbol{Q_{PV}})$ and terminal voltage ($|V_{PV}|$, δ_{PV}) in Figure 2 as follows:

$$P_{PV} = \frac{|V_{An}||V_{PV}|sin(\delta_{An} - \delta_{PV})}{X_{PV}}, \; Q_{PV} = \frac{|V_{An}||V_{PV}|cos(\delta_{An} - \delta_{PV}) - |V_{PV}|^2}{X_{PV}} \quad (1)$$

From (1), then δ_1 and $|\boldsymbol{V_1}|$ can be computed.

$$\delta_{An} = \delta_{PV} + atan\left(\frac{P_{PV}.X_{PV}}{Q_{PV}.X_{PV} + |V_{PV}|^2}\right), \; |V_{An}| = \frac{P_{PV}X_{PV}}{|V_{PV}|sin(\delta_{PV})} \quad (2)$$

3.2. Inclusion of battery as the storage unit

The battery can be assumed as a constant voltage source with fixed amount of energy and modelled as a constant DC voltage source with series internal resistance. Since the battery has a limitation on the duration of its generated power depending on the amount of current, then it was assumed that the battery is charged at off-peak load periods. The minimum no-load battery voltage is 0V and the maximum battery voltage is equal to 2*E0. The minimum capacity of the battery is 0 Ah and the maximum capacity is Q-max. The equivalent circuit of a generic dynamic battery model parameterized to represent most popular types of rechargeable batteries is shown in Figure. 3. Battery as the storage unit with appropriate is including into the algorithm of Figure 4 and their charge/discharge strategies is coordinated with rooftop PVs to further improve the network voltage profiles.

3.3. DC-DC converters

Due to power the DC residential households, the AC voltage from the grid has to be converted into DC. A centralized boost rectifier is utilized to convert 240V AC to 380VDC. Therefore, any devices utilizing the high voltage (HV) component of the micro-grid unnecessarily require rectification at each point of use, and ensure the maximum efficiency. Also by utilizing centralized rectification, the grid rectifiers are designed for higher load and capacity, which improves efficiency [12] as shown in Figure 5.

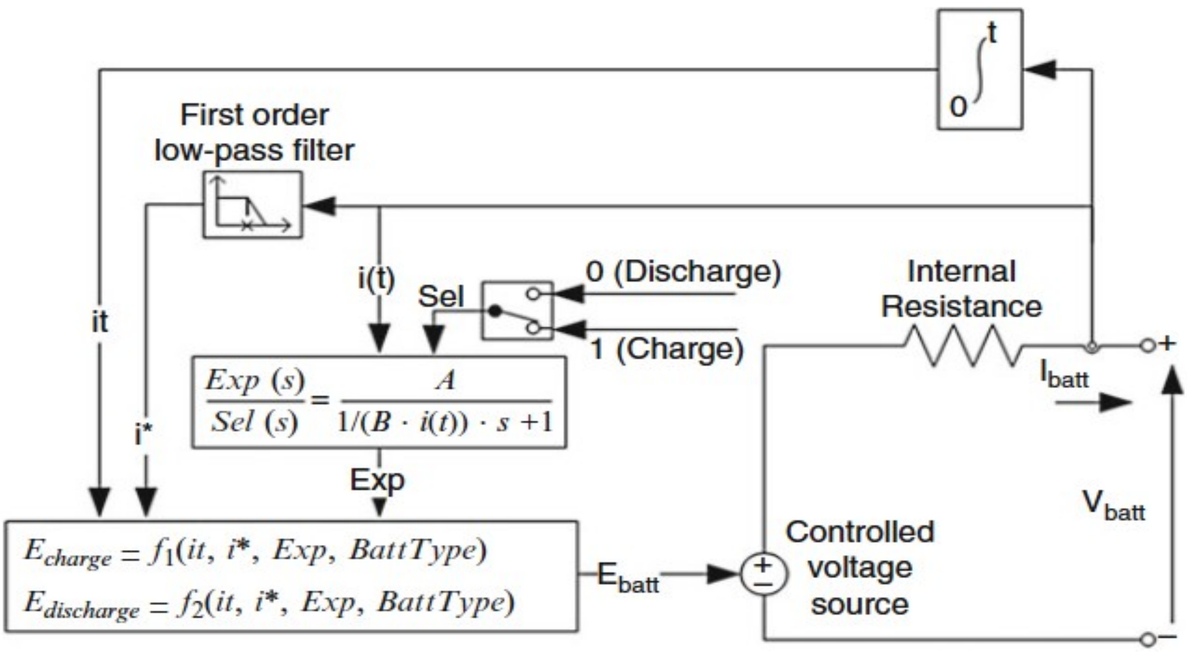

Figure 3. Equivalent circuit of battery

ISSN No. 2356 – 2536
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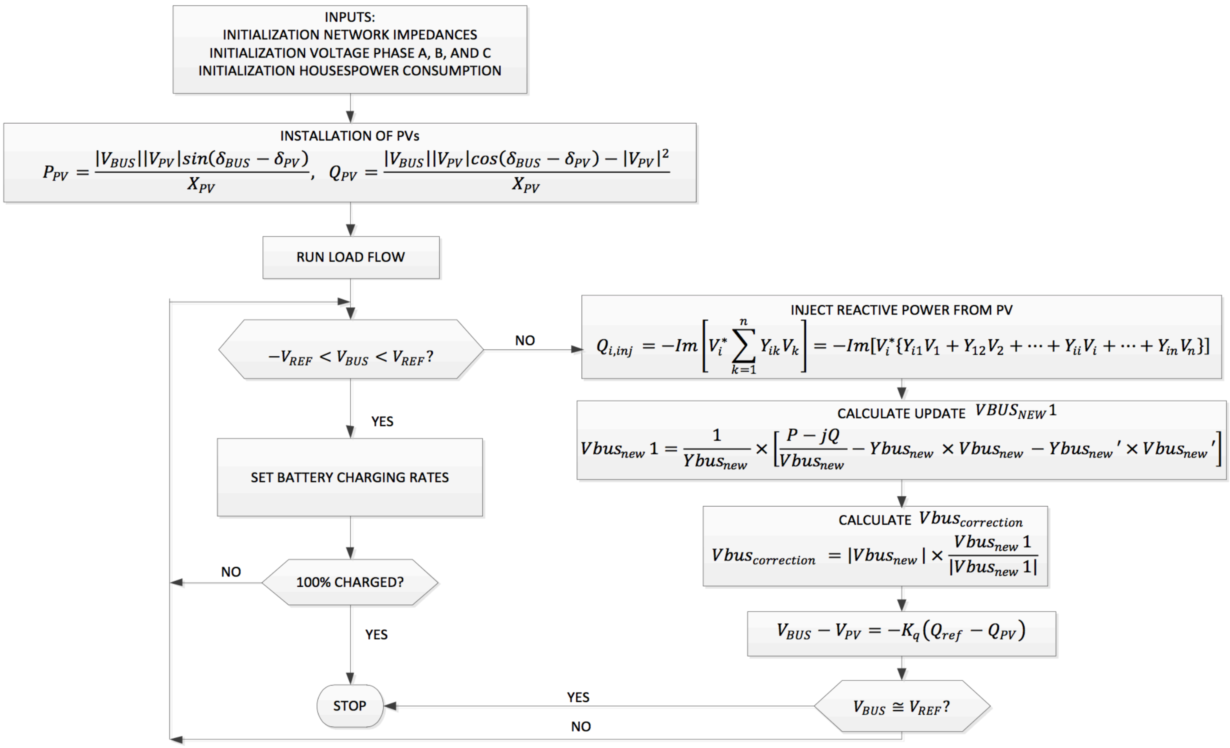

Figure 4. Flow chart of coordinated rooftop PVs and battery

3.4. DC loads

At the end of the DC distribution feeder are the loads of the DC House. The main residential load is predominantly lighting. Due to advances in LED technology, it is now possible to have DC light bulbs that are energy efficient and low-cost. Other loads that a household currently has might be a fridge, a washing machine, iron, television, laptop, crockpot, fan, air conditioning and a microwave oven.

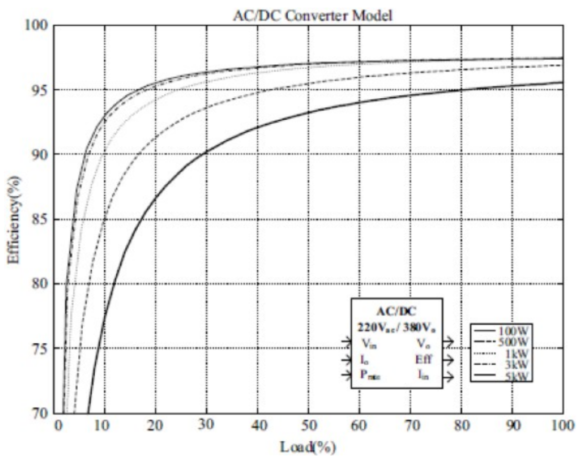

Figure 5. Rectification model efficiency [12]

3.5. Configuration of the proposed DC household system

Figure 6 illustrates the entire configuration of the DC distribution system for households using single-phase rooftop PV.

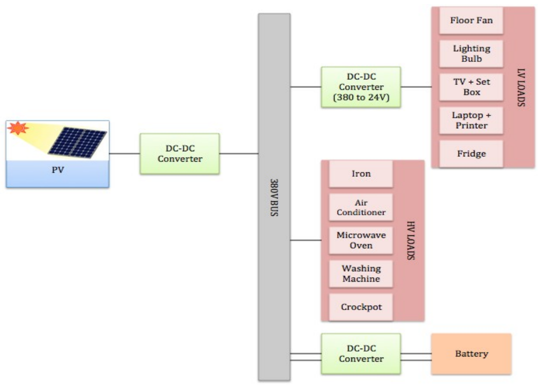

Figure 6. Configuration of proposed DC distribution system supplies household.

The system consists of two major components: the 380V HV and 24V LV. The external grid is expected to be the supplying the majority of energy to the household, which is

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220-240VAC source. The DC-DC converter (rectifier) converts AC voltage to DC and enter through the HV component, and another DC-DC converter converts the 380V to 24V for the appliances that operate at 24V. The voltage ratings of the rectifiers and converters depend on the requirements of the household.

3.5. Integrated the proposed DC distribution system into unbalanced three-phase system

As the proposed DC households developed, their integration into the residential distribution feeder is illustrated in Figure 7. The author has proposed a coordinated technique of the distributed single-phase rooftop PVs with the rating of 1-5kW randomly in the unbalanced three-phase LV feeder in Safitri et al., [13]. All residential households loads are assumed as constant power type for simplicity. It is to be noted that although the number of houses is same for all phases, their instantaneous power consumption is different which makes the system unbalanced. It is assumed that each house may have a rooftop PV system connection. However, as PVs have different ratings, it further makes the system unbalanced.

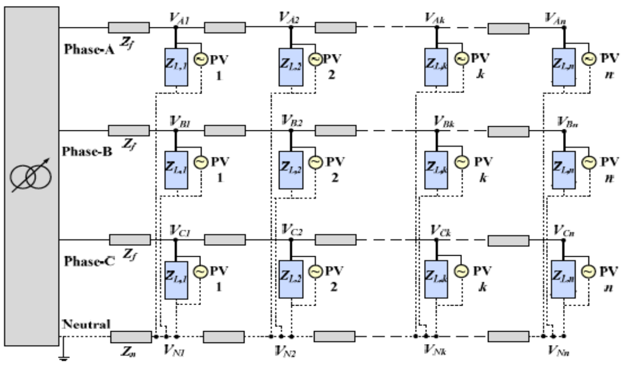

Figure 7. Unbalanced three-phase residential LV network with single-phase rooftop PVs [13]

The selected test network is a three-phase four-wire radial LV residential feeder, with *N* buses, that is supplied from a three-phase three-wire medium voltage feeder through a three-phase *Dyn* distribution transformer, as shown in Figure 7. The LV feeder is assumed to be a common multiple earth neutral (CMEN) system [14] in which the neutral wire is earthed at the distribution transformer as well as at the premises of each load. All residential households loads are assumed as single-phase type, which are distributed equally among the three phases of the network. Assuming the LV feeder is constructed from All Aluminium Conductor (AAC) overhead types that are distributed over cross-arms with vertical configurations over the poles. Also assuming the after diversity maximum demand (ADMD) of 4.7kVA for each residential house and length of 400 meters for the lines, the transformer ratings and conductor cross sections are selected based on engineering judgments.

As the DC power source side has been configured and determined in Safitri et al., [13], then by modifying the load side, several simulations can be developed into this proposed DC distribution system and unbalanced three-phase residential households.

4. RESULTS AND DISCUSSIONS

The simulations mostly conducted in Matlab. The results have been organized as the power source side, which is PV penetration level of residential households feeder, and DC loads side. Any considered rectifiers would be conducted as author's future work.

4.1 PV penetration under consideration

As author's previous work [13], PV cells are assumed to have an equivalent distribution of 1-5kW while the PV inverters are assumed to have a capacity of 140% of the PV cells. In this study, the sunlight availability is assumed between 6am and 6pm while the PVs generate their maximum output at 12pm. To consider the clouds effect on the PV output power generation, a white noise signal is added to the output power of the PVs. Figure 8 illustrates the considered PV output power for the duration of this study. Since the PVs are located in a close geographic area (400m) the same PV output power characteristic is used for all considered PVs in the network.

Then the penetration level of PV is determined by its base average, linear optimum average, and non-linear optimum average, respectively. Figure 9 illustrates the 25% to 100% penetration PV levels for the mentioned averages. Figure 9 shows the increasing of PV penetration during the middle of the day while the PVs are producing actual power. The increase counteracts the voltage sag that would otherwise exist with no PV output. The linear dispatch is significantly maintains the voltage within its standard limit for most of the day for a PV penetration level over 50%.

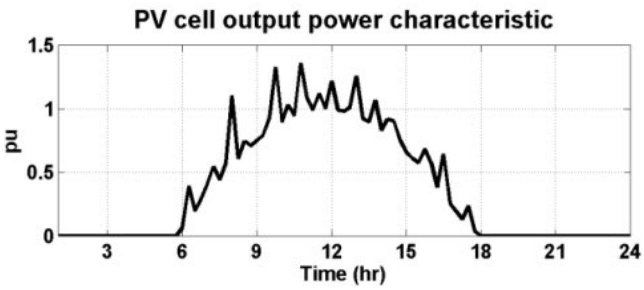

Figure 8. The considered PV output power over a 24-hr period

ISSN No. 2356 – 2536
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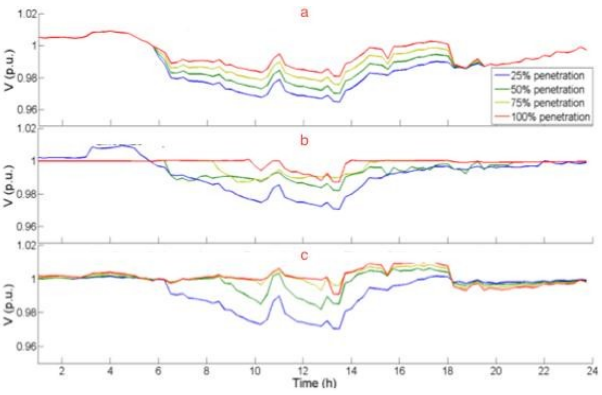

Figure 9. Feeder Voltage at different PV penetration levels in 24 hours period; a. Base average, b. linear optimum average, c. non-linear optimum average

Table 3.
Total consuming energy for DC based appliances

DC based Appliance	Watts	Hours/day	Watt hours
Floor Fan	40	12	480
Lighting Bulbs	80	8	640
Washing Machine	180	2	360
TV + Set box	60	6	360
Fridge	80	24	1920
Laptop + Printer	75	6	450
Iron	120	1	120
Air Conditioner	240	8	1920
Crockpot	100	1	100
Microwave Oven	120	2	240
Total energy			6590

4.2. DC loads energy consumption and efficiency

Similar to the AC voltage, high-powered loads is designed to utilize the larger 380V DC to reduce the current requirement and maximize the efficiency. The manufacturers of the appliances provide these voltage requirements. For this research, high power usage appliances (e.g. air conditioning systems, microwaves oven, iron, and crockpot) must connect to the 380V bus and low power appliances (e.g. TVs, lighting, fridge, laptops, floor fan and washing machine) connect to the 24V bus. Table 2 and 3 show the total consuming energy (Watt-hours) of each selected AC and DC based appliances, respectively.

Table 2
Total consuming energy for AC based appliances

AC based Appliance	Watts	Hours/day	Watt hours
Floor Fan	160	8	1280
Lighting Bulbs	150	8	1200
Washing Machine	350	2	700
TV + Set box	100	6	600
Fridge	100	24	2400
Laptop + Printer	160	6	960
Iron	600	1	600
Air Conditioner	750	8	6000
Crockpot	200	1	200
Microwave Oven	1200	2	2400
Total energy			16340

As can be seen from both Table 2 and 3, energy used between AC appliances and DC appliances are significantly reduced. The experiences are illustrated in Figure 10. Blue line represents AC based appliances and red line represents DC based ones.

Furthermore, the energy consumption of each appliances categorized as its types. For examples, air conditioning and floor fan are categorized as non-controllable appliances, fridge and crockpot are categorized as permanent appliances, washing machine and microwave oven are programmable appliances, heater and lighting bulb are heater element appliances, last but not least, television set and laptops are rechargeable appliances. Figure 11 shows the consumed energy of those categorized appliances within 24 hours.

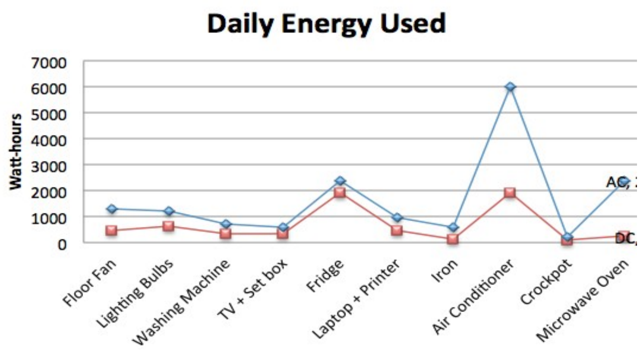

Figure 10. Comparison of energy used by the AC and DC appliances.

Mostly for high power usage appliances (e.g. air conditioning systems, microwaves oven, iron, and crockpot) that connected to the 380V bus, the efficiency of DC based appliances is massive than the AC ones. While for low power appliances (e.g. TVs, lighting, fridge, laptops, floor fan and washing machine) that connected to the 24V bus, is vice versa. Figure 12 illustrates the efficiency of both AC and DC appliances.

ISSN No. 2356 – 2536
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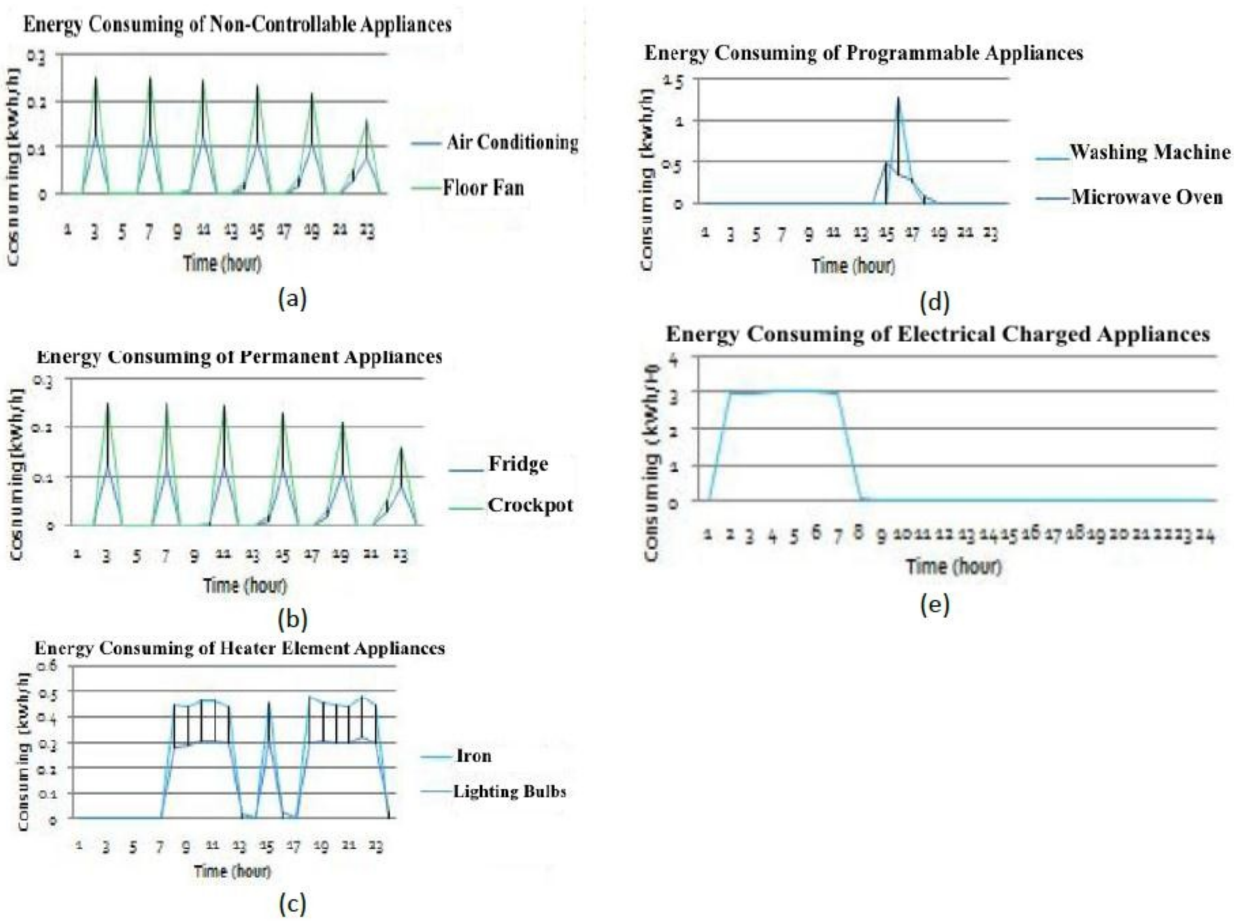

Figure 11. Energy consuming within 24 hours of categorized appliances; (a). Non-controllable, (b). Permanent, (c). Programmable, (d). Heater elements, and (e). Electrical charged components.

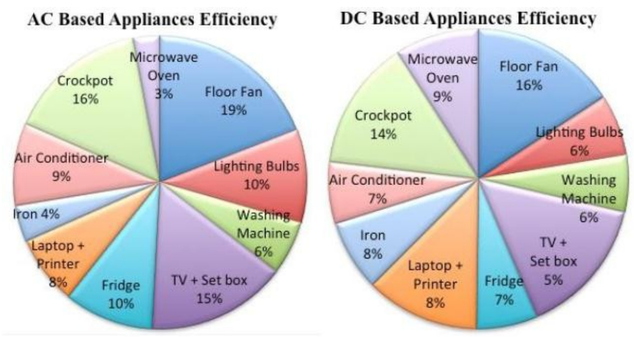

Figure 12. The efficiency of both AC and DC appliances

5. CONCLUSION

This paper presents an integration of DC households distribution system generated by single-phase rooftop PVs into unbalanced three-phase residential feeder. This proposed system is using fewer components, which obviously made it less cost. The design considered the DC power that has been generated by single-phase rooftop PVs within the rating of 1-5kW. At day times, as PV penetrated over than 50%, then it reduced the imbalanced of the three-phase feeder. It also considered the consumer side. The households' appliances were designed as DC operated appliances, where it is divided into 380V and 24V. As the simulation competed, the categorized loads presented the energy consumption within 24 hours and their efficiency. DC households produce better and wiser use of electric energy and obviously less cost.

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