Microgrid for Low Voltage Distribution Systems and a Model for Optimum Power Sharing

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***Abstract*— Grid-connected microgrids have become financially and technically feasible due to the high integration of renewable-based distributed generators and the fast development of battery technology. The formation of microgrids facilitates the integration of multiple sources of energy including renewables such as solar and wind at the distribution level. Since the solar irradiation level in Sri Lanka is sufficient for electricity generation using solar photovoltaics throughout the year, the paper proposes forming microgrids for existing low voltage feeders utilizing solar PV as one of the main micro-sources of energy for the microgrids. Other than solar PV, the proposed microgrid consists of a grid supply, battery energy storage device, and diesel generator. Within this study, an algorithm has been developed to optimally share the energy demand of the low voltage distribution system between utility grid, solar photovoltaics, battery energy storage device, and diesel generator. Based on the proposed algorithm, microgrid simulation software has been developed in the MATLAB-Simulink environment. Formula for the determination of most suitable capacities of micro-sources and battery energy storage device were proposed. The proposed model was tested to transform an existing low voltage distribution system into a microgrid. Optimum power dispatch between the sources of the microgrid during 24 hours of a day has been presented using the developed software. The results show that depending on the time of the day the use of solar PV, battery energy storage device, and diesel generator have more financial benefits than the use of grid energy alone throughout the day.**

Keywords: Distribution systems, microgrid, Rooftop Solar PV

I. INTRODUCTION

Conventional low voltage (LV) distribution systems get electricity from the grid through distribution transformers. Both transmission and distribution networks are utilized in feeding electricity to those distribution transformers. The common problems of energy transportation over a long distance include higher energy losses, low reliability, and low power quality. During the last two decades, the use of renewable energy for electricity generation has significantly increased. It is expected that renewable energy sources will share the major portion of electricity demand in the future [1,2]. Therefore, the number of grid-integrated large, medium, and small-capacity renewable energy-based plants is parallelly increasing. The use of renewable sources for electricity generation at the distribution level reduces the cost for power transmission and improves the distribution system performance including reliability and power quality. Such renewable integration at the distribution level helps to reduce the stress on the transmission systems.

As a tropical country, in Sri Lanka abundant solar energy is available throughout the year. It has been estimated that the annual solar irradiation varies between 1642 kWh/m^2 to 2190 kWh/m^2 across the country [3]. Presently, solar photovoltaics (PV) are mainly used as consumer-owned rooftop solar PV. Such solar PV integration has financial benefits for the consumers when the daytime excess energy of solar PV is sold to the grid. For the utility, this integration reduces stress on the transmission network and improves the voltage at the distribution level. However, the level of rooftop solar PV integration at the distribution level is still low. Especially in rural areas, only a few rooftops solar PVs are observed [4]. From the consumers' perspective, this is because of the non-worthiness of rooftop solar PV installation due to low energy consumption per household, and the consumer's inability to invest capital cost for rooftop solar PV. From a technical point of view, rooftop solar PV integration can cause negative impacts on the distribution system performance as well. This includes voltage unbalance, overvoltage issues, reverse power flow, etc. [5]. Therefore, even in the areas (especially in urban and semi-urban areas) where there is high demand for rooftop solar PVs, utility organizations restrict the maximum capacity of the solar PVs.

Microgrid is a distribution system including various renewable energy resources that can deal with higher penetration of distributed generators in power systems [6]. The microgrids are formed utilizing different types of renewable energy sources plus energy storage devices that make smart grids [7,8]. [8] stated that when a grid-connected microgrid consists of two or more dispatchable energy sources, the grid operator must run the system economically. Therefore, for a microgrid with multiple sources, the criteria for the optimum power dispatch becomes the minimum generating cost of the sources considering various constraints. It is important to have a controlling mechanism within the microgrid for optimum power sharing [9]. Battery energy storage device (BESD) play an important role in microgrid operation. This is because BESD can be set to deliver power when the unit cost of other energy sources is high (such as grid energy) for the considered period of the day. [10] assessed the financial viability and successfully implemented grid-connected solar PV with a maximum power point tracking system in Egypt. However, this research considered only the operation of solar PV alone without having BESD which could have been used to store daytime excess energy and utilize it at nighttime. In the meantime, the paper did not discuss any options available when solar irradiation is not sufficient to provide electricity. In the case of off grid microgrids, in addition to renewable sources and BESD, diesel generators (DG) are integrated to ensure high reliability [11]. To make the microgrids economically feasible, power-sharing between the sources must be done optimally.

Solar PVs can be installed at the LV distribution feeder by the distribution system owner. Such feeder-level solar PV can cater to most of the daytime demand of the feeders. Especially, during the period in which solar irradiation level is high. Such an approach can increase the total capacity of solar PVs at the distribution level by resolving non-worthiness and lack of investment from the consumers' point of view. For the maximum economic benefit, and also to be more independent from the utility, solar PVs are integrated with BESD [12].

In this study, feeder-level microgrids that consist of solar PV and BESD are proposed for the existing LV distribution systems. The practical implementation of feeder-level microgrids depends on economic feasibility. The power dispatch between the micro-sources of energy (solar PV, BESD) must be carried out optimally so that the microgrid brings financial viability to the utility organization. Generally, LV distribution systems are radial networks consisting of 3-7 feeders. When they are transformed into microgrids, consumer-oriented reliability, and power quality will be improved. The reduction of high burden for distribution transformers, uninterrupted supply of electricity to the consumers, delaying the construction of large capacity power plants, and reduction of greenhouse emission of gases are the main advantages of grid-connected microgrid systems [3]. These advantages are important for countries like Sri Lanka in which capital investments are mainly through loans. The operators of microgrids can reduce system operating costs while enhancing their reliability and environmental performance. [13,14] presented the optimum sizing of various energy sources of the microgrid, including solar, wind, and BESD.

Most of the urban distribution systems are interconnected or ring systems. Nevertheless, the practicality of constructing solar PVs and BESD is low due to space limitations. Hence, this study mainly focuses on LV distribution systems in rural areas. The objective of this research is to propose a feeder-level microgrid simulation model for exiting LV distribution systems to economically dispatch power among the micro sources of the microgrid by considering technical constraints. The proposed model can replace many of the conventional LV distribution systems in Sri Lanka. This also can be used for distribution systems in another country with similar conditions. The sources of the proposed model are solar PV, utility grid (UG) (through the distribution transformer), DG, and BESD

The LV feeder consists of three sources of energy (solar PV, UG, DG) plus a BESD. When a microgrid operates without DG, it is identified as an environment mode of operation. This is because the greenhouse gas emission is nearly zero. In this mode, there can be four modes of operation: Energy only from the UG; Energy from UG and solar PV; Energy from UG, BESD, and solar PV; Energy from UG plus BESD. When a microgrid operates together with DG to achieve a minimum cost of generation, such a mode of operation is identified as an economic mode. In this mode, there are four modes of operation: UG and DG; UG, DG, and Solar PV; UG, BESD, DG; UG, solar PV, BESD, and DG. This study proposes combined scheduling of the two modes of operation. Feeder loads include domestic loads and loads of other establishments such as schools, post offices, shops, etc.

II. METHOD

Most of the LV distribution systems in rural and semi-urban areas have a higher percentage of domestic consumers and therefore the distribution transformers have peak demand between 18:30 and -21:30 h [15]. In this study, the daily load curve of the LV distribution system is considered a step curve with 15-minute intervals. It is assumed that all the consumers of the LV distribution system use time of use tariff (TOU) with three rates based on the time energy consumption [15]: peak (18:30-22:30), Day (05:30-18:30), off-peak (22.30-05.30). The solar irradiation curve is also presented as a step curve with 15-minute intervals.

A. *Structure of the Proposed Model*

The proposed structure of the microgrid is shown in Fig.1. UG connects to the microgrid via a point of common coupling (PCC). The PCC is the point across which electricity is supplied to the load or returned to the UG depending on whether the microgrid has an excess or deficit of electrical power for the given moment. The controller executes the function of optimum power sharing between the sources of the microgrid while ensuring the power balance at any instant in time. The power electronic interface mainly contains inverters that convert the DC power of either solar PV or BESD to AC power. Based on the requirement, the DG provides power to the load. During the daytime, solar PV generates electricity depending on the solar irradiation level. BESD's charge is based on energy of solar PV availability, and its discharge is based on the cost of energy and energy availability.

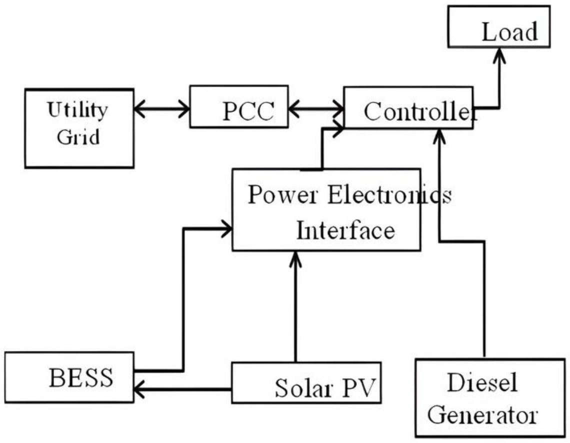

Figure.1. Proposed structure of the Microgrid

B. Capacity Determination of Sources in Microgrid

1) Solar PV

Energy generated from solar PV is delivered to meet the daytime demand (total demand or part of it) of the LV distribution system. Solar irradiation depends on weather conditions, time of the day, etc. Therefore, the energy generated from solar PVs is uncontrollable. Solar PV capacity ($P_{solar\ PV}$) was calculated based on the distribution transformer's capacity and the average power factor of the LV distribution system. $P_{solar\ PV}$ is given in equation (1).

$$P_{solar\ PV} = S_T Cos\varphi_{av} \quad (1)$$

Where

S_T Distribution transformer capacity (kVA)

$Cos\varphi_{av}$ Average power factor of the LV distribution system

The unit cost of energy of solar PV (C_{PV}) (in Sri Lankan Rupees (LKR) per kWh) is calculated based on the total investment and maintenance cost and total energy generated by the solar PV over its lifetime. The investment cost is determined considering the cost of fixing one unit (C_{kW}) of solar PV including other associated equipment such as cables, inverters, etc. The energy of the solar PV during its lifetime is determined considering the reduction of panel efficiency over time. TheC_{PV} is given in equation (2).

$$C_{PV} = \frac{C_{kW} \times n}{W_1 + W_2} \quad (2)$$

Where

C_{PV} Cost of energy of solar PV (LKR/kWh)

C_{kW} Capital and maintenance costs for solar PV of 1 kW (LKR)

n- Number of kW units

$W_1 + W_2$ - the energy of solar PV with higher and lower efficiency over the lifetime

2) Diesel Generators

Electricity generation from solar PV highly depends on the weather conditions. During rainy and cloudy days, the output of solar PV becomes less than on sunny days. In a certain period of the year, this cloudy atmosphere can continue for several days. This affects the BESD's operation. Therefore, a DG has been included to provide electricity to the LV distribution system to provide uninterrupted electricity considering minimum cost criteria. DG can share part of the load together with the other sources based on the unit cost of energy and availability of the energy at the given time. The DG's capacity was determined based on the maximum load of the LV distribution system. The unit cost of energy of DG is calculated based on the cost of fuel consumption at various loading, capital cost, operating, and maintenance

3) BESD

Since the daytime energy consumption by the LV systems is low, there is an excess of energy generated from solar PV. This excess energy is used to charge BESDs. The capacity of the BESD was calculated to provide continuous peak power for three hours. The capacity of BESD is given in equation (3).

$$C_{BESD} = \frac{P_{max} \times T}{V_{rated} \times \eta \times K} \ [kAh] \quad (3)$$

Where:

C_{BESD} Battery capacity of the required configuration (Ah)

P_{max}- Peak Power; W

T continuous discharging time (h)

V_{rated} Battery rated voltage; (V)

η Battery inverter efficiency

III. ECONOMIC POWER SHARING ALGORITHM

During the daytime (06:00 to 18:00 h), the main energy source is solar PV. If the solar PV energy is not sufficient to meet the energy demand of the given period, either BESD or UG, or both together dispatch the remaining amount of energy of the load. The selection of the type of source (UG or BESD) was based on the cost of the energy which depends on the time. In addition, technical limitations due to the state of charge of the BESD and fuel availability of the DG have been considered when BESD and/or DG contribute to making the power balance. When BESD does not possess sufficient energy charge to meet total energy, the remaining energy is delivered by either UG or DG based on the unit cost. If solar PV has excess energy over the load, that energy is used to charge the BESD. If the BESD is fully charged, the excess energy of solar PV is fed back to UG.

When solar energy is not available (18:00 h to 06:00 h), the UG, BESD, and DG dispatch power to the load considering the cost of energy. The energy cost of BESD is a constant value. However, its energy discharge depends on the state of the charge. Batteries are not intended to deliver energy greater than the depth of discharge. This value is taken as 80% of its rated capacity. DG running cost (which is the cost of fuel) depends on the amount of power delivered by the generator. The available power of both BESD and DG is reduced while they dispatch the energy. Therefore, after the cost comparison, the energy availability at the given period is verified. This can lead to the operation of a combination of energy sources.

A detailed flow chart of the algorithm for optimum power sharing is shown in Fig. 2. Using the above algorithm, the grid-connected microgrid system was simulated using MATLAB-SIMULINK environment and shown in Figure 3.

The criteria for optimum power dispatch between the sources of the microgrid is the minimum cost of energy for the considered period. The microgrid consists of three sources of energy. In addition, BESD delivers or consumes electrical energy based on its discharging or charging mode. Dispatch of power by the single or multiple combinations of these energy sources (solar PV, DG, UG, and BESD) to meet the total demand is based on two main factors: energy availability and the cost of energy.

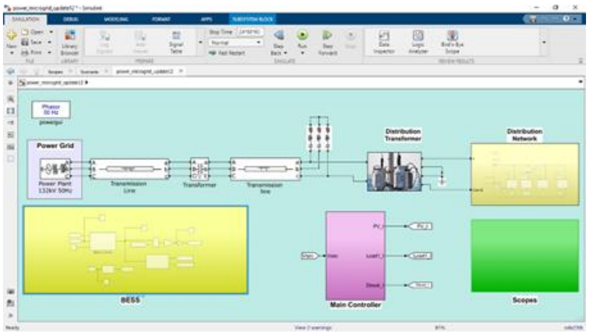

Figure 3. Microgrid simulation model based on the optimum power sharing algorithm

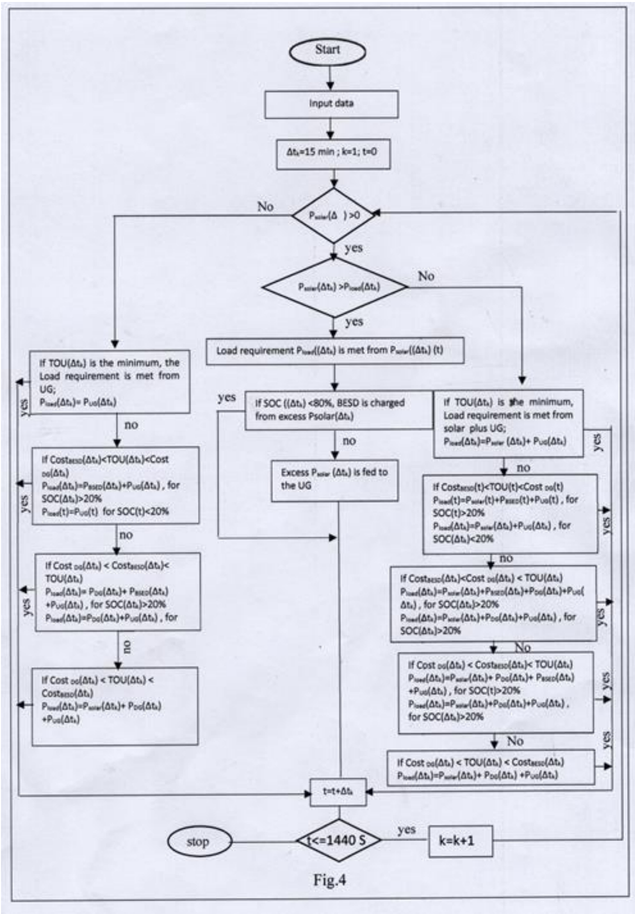

Figure.2. Algorithm for Optimum power sharing between the sources of microgrid.

IV. CASE STUDY

The proposed method was applied to form a feeder-level microgrid for a rural LV distribution system. A LV distribution system with 160 kVA, 11 kV/400 V distribution transformer was selected as the test case. Daily load variation in each 15-minute interval was measured at the LV side of the distribution transformer. Capacities of the solar PV, BESS, and diesel generator and their unit cost of ' energy was calculated as per the formula (1), (2), and (3) and given in Table I. The solar irradiation curve of the area has been considered for calculating energy generated from the solar PV array. The time of use tariff (before the tariff revision in 2023) is given in Table II.

TABLE I. CAPACITY AND COST OF ENERGY OF THE SOLAR PV, BESS, AND DG

Source of energy	Capacity	Unit Cost (LKR[a.] / kWh)
Solar PV	128 kW (2 x 64 kW inverters)	4.56
BESD[b]	3500 Ah (18 of 12 V, 200 Ah batteries)	4.62
Diesel Generator	80 kVA	38.65 @ full capacity 40.27 @75% of the capacity 44.47 @50% of the capacity

TABLE II. TIME OF USE TARIFF SCHEME

	Time of the day (h)	Tariff LKR./kWh
Off-peak	22:30-05:30	13.00
Day	05:30-18:30	25:00
Night peak	18:30-22:30	54:30

V. RESULTS AND DISCUSSION

The optimum power dispatch between the sources plus the load curve snapshots obtained from the simulated model are shown in Fig. 4 and Fig.5. provides the power dispatch of each source and load as separate graphs. In Fig. 7 the power dispatch of all the sources throughout a day is given as a single graph. The day summary of the microgrid showing all the power variations and the costs obtained from the simulated model are shown in Fig. 6. It demonstrates all the relevant information of the microgrid including unit cost of energy of the microgrid sources and cost variation throughout the day. This also includes tariff, solar irradiation of the day, and average load during the peak, day, and off-peak durations of the day.

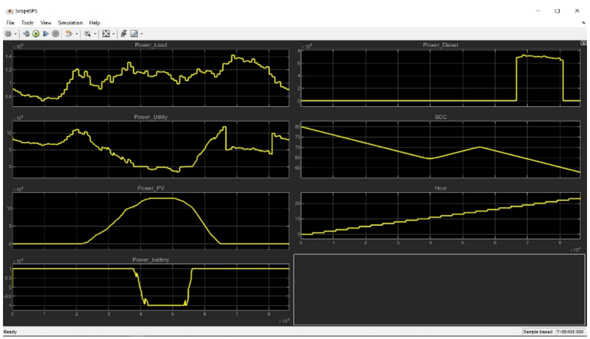

Figure.4. Load profile, power delivered by the utility, solar PV energy generation, state of charge of the battery during 24 hours of the day

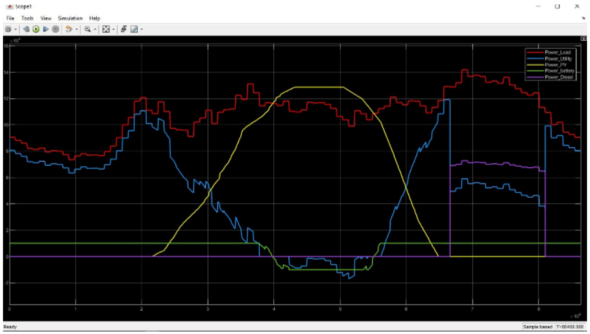

Figure.5. Economic power dispatch between the sources given in the same graph obtained using the algorithm

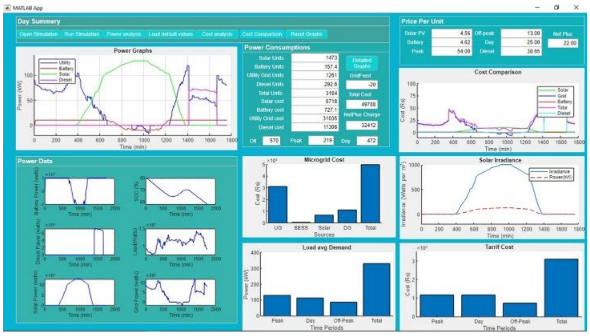

Figure.6. Day summary of the microgrid that shows power dispatch, the energy cost of the sources, power during peak, off-peak, and day time, and tariff structure

VI. CONCLUSION

This study showed that the feeder-level microgrid and a proposed method of power dispatch reduce the use of grid energy to meet the demand of the distribution system. It also shows the cost-effectiveness of the solar PV-BESD combination for meeting the energy demand of the distribution systems. So, the proposed microgrid fully utilizes the energy of solar PV which is cheaper and environmentally friendly. Despite the negative effects on the environment, utilization of DG during the night peak reduces the cost of energy. Apart from the economic power dispatch, the formation of microgrids influences the increase load point reliability and system reliability. Implementation of such microgrid models at the LV levels will help achieve one of the sustainable goals in Sri Lanka: by 2030, meet seventy percent of the electrical energy demand of the country from renewable sources of energy

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