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Economic Model for Solar PV Integration at LV Distribution System Level

K.A.C. Udayakumar[1], P.H.R.Y.Paranahewa [2],
[1](Department of Electrical and Computer Engineering/ The Open University of Sri Lanka, Sri Lanka)
[2](Department of Electrical and Computer Engineering/ The Open University of Sri Lanka, Sri Lanka)

Abstract: *This paper investigates economic benefit of parallel operation of battery integrated solar PV system and grid to meet the electricity demand of low voltage distribution systems. Power of solar PV has been considered as a time variable function. Considering the power limits of the solar PV which is based on the solar irradiation level, power dispatch equations for grid and solar PV systems are presented. The proposed method of power sharing between parallel operating sources is presented in a flowchart. The method has been tested for a low voltage radial distribution system. Capacity of Solar PV and the Battery energy storage system and the cost of energy have been calculated. Based on the results the economic benefit of the proposed method has been analyzed.*

Key words: *Solar PV, Battery Storage, Power dispatch, Low voltage distribution system*

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I. Introduction

Solar photovoltaic (Solar PV) has become one of the major renewable sources of energy for electricity generation in many tropical countries including Sri Lanka. Solar PV are used both at distribution (mainly as roof-top solar PV) and grid levels (as solar farms). At present, the use of solar PV in low voltage (LV) distribution systems (400V/230 V) is limited to operation of rooftop solar PV at the consumers' residences. Therefore, Solar PV penetration in distribution systems depends on consumers desire, affordability and level of benefit. Average monthly energy consumption of domestic consumers in many of rural and semi urban areas are comparatively low and most of the consumers in these areas are not interested in investing money to have solar PV in their rooftops. Therefore, contribution of solar PV to total generation in LV distribution systems in rural and semi urban areas remains at low level. Other possibility of increasing solar PV at distribution level is connecting the solar PV panels to the feeding point of the low voltage distribution system. The solar PV is then owned by either distribution licensee or utility organization. In such scenario, the LV distribution system has the options of receiving electricity either from grid or solar PV. Power dispatch between these two sources of energy (grid and solar PV) is based on the cost of energy and availability of energy. Cost of grid energy and energy availability from solar PV are functions of time. From the solar PV side, the amount of energy generated at a time depends on the solar irradiation. Since load also a time variable there can be deficit or excess of solar PV energy while fulfilling energy requirement of the LV system. When there is an excess of solar PV energy, energy storage device is used to store this energy to be used later when the demand of the system is high. In this study battery energy storage systems (BESS) has been used as energy storage device. Economic power dispatch between these two sources of energy during a day has been carried out considering the power limits of the solar PV. Since BESS is integrated to the solar PV system, the night peak demand is shared by grid and the BESS.

At any instant of time there should be a balance between total energy generation and the demand of the system. Both solar PV generation, load of the distribution system are time variables. Cost of solar PV energy is a constant value, but the cost of grid energy depends on the time of the day. The cost of grid energy during peak hours is higher than that of off-peak hours. Generally, in economic power dispatch between parallel operating sources of similar type should have the minimum and maximum power limits [1][2]. However, at the LV distribution level, with respect to the total load of the distribution systems the capacity of the grid is much higher. Therefore, grid energy does not have minimum and maximum power limits while solar PV energy has maximum power limit. Considering these limitations power dispatch equations have been presented to meet the demand in most economical way. Since the solar energy is available only during the daytime power balance equations for daytime and nighttime are presented separately.

II. Material and Methods

In the proposed model electricity demand of the distribution system is met by the generation of electricity from either one or both energy sources: grid and solar PV. At a given time the amount of power dispatch to the load by each of these sources is determined by two main factors: energy availability and the cost of the energy. In this model BESS is integrated to the solar PV system and the excess of the energy from the solar PV is delivered for charging the BESS. The energy stored in the BESS is discharged during the night peak when the cost of grid energy is high. The losses in the LV distribution network have been ignored and economic power dispatch during twenty four hours of a day is determined. It is also assumed that the energy generated from the solar PV is fully utilized by the load of LV distribution system and BESS, and therefore, reverse power flow from the LV distribution system to the grid has not been considered. The proposed model of power dispatch is given in figure 1.

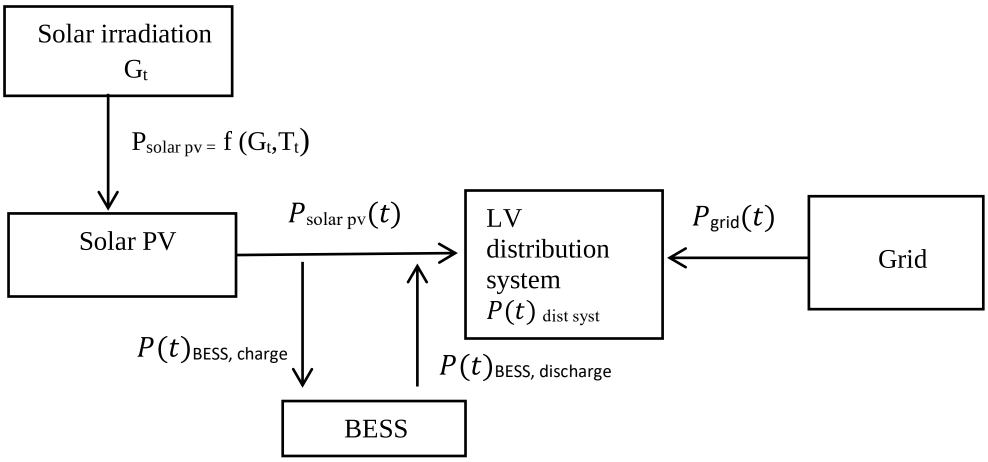

Fig.1. Proposed model of distribution level solar PV integration

Power dispatch between the grid and solar PV can be expressed as given in equations (1), (2).

$$P_{\text{grid}}(t) + P_{\text{solar pv}}(t) = P_{\text{dist syst}}(t) + P_{\text{BESS, charge}}(t);\ P_{solar\,pv}(t) \leq P_{\text{PV max}};\ t = \{6 \ldots \ldots 18\ hours\} \qquad (1)$$

$$P_{grid}(t) + P_{\text{BESS, discharge}}(t) = P_{dist\,syst}(t);\qquad t = \{18 \ldots \ldots 6\ hours\} \qquad (2)$$

Where

$P_{dist\,syst}(t)$	-Total demand of the LV distribution system
$P_{grid}(t)$	- Power delivered by the grid;
$P_{solar\,pv}(t)$	- Power delivered by the solar PV
$P(t)_{\text{BESS}}$	- Charging/ discharging power of BESS
$P_{\text{PV max}}$	- Maximum power of the solar PV

Power delivered by the solar PV ($P_{\text{solar pv}}(t)$) depends on the solar irradiance and the temperature. This is given in equation (3)

$$P_{\text{solar pv}}(t) = \text{f}\,(\text{Gt, Tt}) \qquad (3)$$

Where:

Gt – solar irradiation in the location at time t (W/m2);
Tt –temperature in the location at time t (°C)

Criteria for dispatching power between the two sources of energy is minimum cost for energy. Cost of solar PV ($C_{\text{solar PV}}$) energy is a constant value and grid energy has different values depending on time of the day. Grid power Pgrid (t) does not have a limit, but the power generated from solar PV has a maximum limit. The load curve of the LV distribution system is considered as hourly step curve and the losses in the system have been ignored. Solar irradiation for one hour is assumed as a constant value. When $C_{\text{solar PV}}$ is less than the cost for grid energy, power of solar PV is dispatched to meet the demand. If the demand at the given time interval is greater than the maximum possible power from the solar array, the rest of power required by the distribution system is taken from the grid. This happens early hours and late hours of the daytime when the solar iiradiation is low. In the event the cost of energy of solar PV is greater than the cost of energy from grid, the solar PV can be used for the charging of the BESS. During the night peak (1800 hrs -22 hrs) power is taken from the grid and BESS. Rest of nighttime power is delivered by the gird. This method of power dispatch during twenty fours per day is presented in a flow chart shown in figure 2. For a given LV distribution system capacity [3] and cost of solar PV, size and cost of BESS need to be calculated before determining the power dispatch schedule for the LV distribution system.

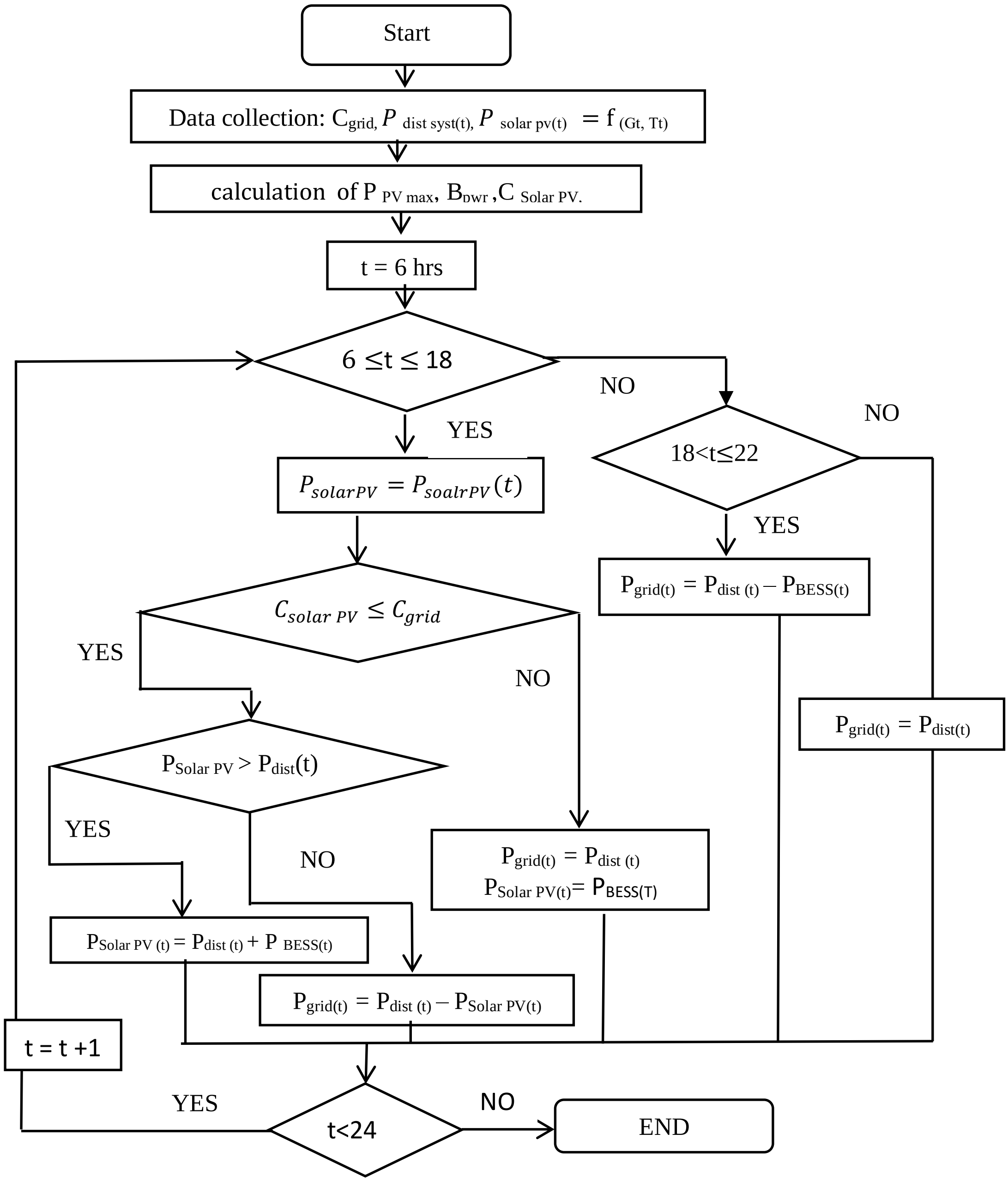

Fig.2. Flow chart of power dispatch of solar PV integrated LV distribution system

Solar PV capacity and cost

The capacity of the solar PV system has been determined based on the total daytime energy requirement of the LV distribution system. Solar PV capacity is determined using equation (6).

$$Solar\ PV\ capacity = \frac{Day\ time\ energy\ requirment}{ESH \times \eta_{sys}} \quad (6)$$

Where

ESH – Equivalent sun hours at the location of solar PV based on the average global horizontal insolation of the world; for Sri Lanka, ESH is taken as 6.3 hours [3]

η_{sys} - Solar PV system efficiency account for the losses in various components, cables, inverters, charge controllers etc. The losses in these components vary between 20%-30% [4] and η_{sys} is taken as 75%.

Number of solar panels has been calculated based on the rated capacity of a panel while the series and parallel numbers of the panels have been determined based on the voltage of the solar PV module, DC system voltage , maximum input current and the short circuit current.
The cost of solar PV ($C_{solar\,PV}$) consists of solar PV arrays, inverters, other associated equipment including cable, control equipment etc. This is given in equation (7) [6]

$$C_{solar\,PV} = C_{pv} + C_I + C_{InvR} + C_{raking} + C_{other} + C_p + C_T + C_{land} + C_{install} \quad (7)$$

Where,

C_{pv} -cost of solar panels
C_I -cost of Inverters
C_{InvR} - inverter replacement cost after 10 years
C_{other} - other equipment (C_{pv} x15%)
$C_{racking}$ - cost for racking work (C_{pv} x5%)
C_p -Preventive maintenance cost (C_{pv} x 5%)
C_T - miscellaneous and Transportation
C_{land} -Cost of land
$C_{install}$ -Installation cost

Hourly energy output of the solar PV system has been determined using equation (8) [4]

$$W\ soalr\ PV\ (t) = A \times r \times H\ (t) \times PR \quad (8)$$

Where,

E -Energy output (kWh) A -Total solar panel Area (m2)
H -Average hourly solar radiation (kWh/m^2) r -solar panel efficiency (%)
PR - Performance of the solar PV System including BESS capacity and cost

BESS capacity and cost

Capacity of BESS has been determined based on the part of the peak power that is to be delivered by BESS by discharging its stored energy. Discharge energy of BESS ($W_{discharge}$) is calculated using equation (9)

$$W_{discharge} = P'_{max} \triangle T_{max} \quad (9)$$

Where,

P'_{max} – Part of the peak power delivered by BESS
ΔT_{peak} – Peak power duration
$W_{discharge}$ -Discharge energy of the battery

BESS capacity (B_{BESS}) is determined using equation (10)

$$B_{BESS} = \frac{W_{discharge}}{DOD}\ (kWh) \quad (10)$$

Where

DOD – Depth of Discharge of BESS

The capital cost of BESS includes cost of battery units, other associated equipment including charge controller, cable, control equipment etc. The operational and maintenance cost also is a part of the total cost of BESS (**C_{BESS}**). This has been determined based on the equation (11)

$$C_{BESS} = B_{rated} \times C_1 + B_{rated} \times C_{op} \times t_1 + k \times B_{rated} \times C_1 + C_r + C_T + C_M \quad (11)$$

Where:

B_{rated}	– Rated capacity of the batteries (kWh)
C_1	- Cost per kWh (Rs)
Cop	- Operation cost per kWh
t_1	- life time of the battery (number of years)
k	- Percentage of associated equipment
Cr	- replacement cost
C_T	- Transportation cost
C_M	- maintenance cost

Lifetime of the battery has been considered as five years. The suitable battery type is taken as Lithium Ion battery. Solar PV system lifetime considered as 20 years therefore replacement cost for batteries in 6th, 11th and 16th years also have been incorporated.

III. Case Study

Proposed method has been tested for a LV distribution system which is fed by the grid via 160 kVA, 33 kV/0.4 kV transformer. Hourly load curve of the distribution system is shown in figure 3.

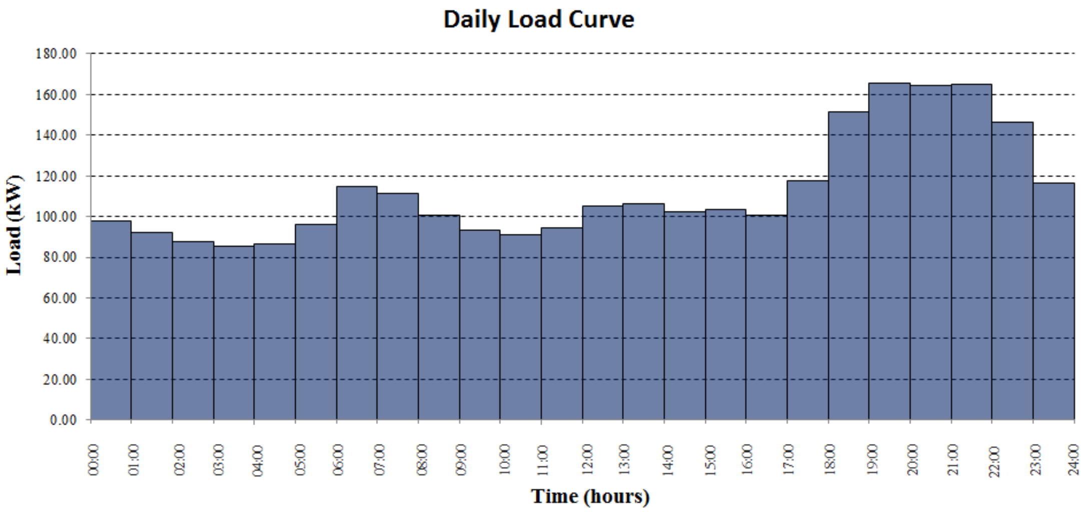

Fig.3: Daily Load Curve of distribution system

Daily average solar irradiation data of the location obtained from the meteorological department is given in the table 1.

Table 1: Daily Average Solar Radiation data

Hour	G_t (W/m^2)	Hour	G_t (W/m^2)	Hour	G_t (W/m^2)
00:00	0.00	08:00	181.89	16:00	483.89
01:00	0.00	09:00	371.70	17:00	283.33
02:00	0.00	10:00	518.44	18:00	97.41
03:00	0.00	11:00	662.89	19:00	7.75
04:00	0.00	12:00	791.43	20:00	0.00
05:00	0.03	13:00	848.36	21:00	0.00
06:00	0.06	14:00	803.17	22:00	0.00
07:00	37.74	15:00	669.46	23:00	0.00

IV. Results

Solar PV capacity for the distribution system has been determined based on the equation (6). Details of the solar PV system and its cost are given in table 2.

Table 2: Details of the solar PV system and its cost

Description	Value
Energy requirement from the solar PV*	1293 kWh

Solar panel rated capacity	340 W
Panel efficiency	17.52 %
Open circuit voltage of solar panel	46.1 kW
Short circuit current of the panel	9.5 A
Maximum input current to the inverter	140 A
Total number of panels in the array	756 (18 x 42)
Invert capacity	225 W(3 x 75 W)
Land requirement for the solar panels	1466.64 m2

*Since part of the energy goes to the BESS charging the total energy requirement of the solar PV has been taken as the sum of the daytime energy requirement plus discharging BESS energy to meet the part of night peak of the system.

BESS capacity and its cost have been determined using equations (9) – (11). Calculation summary of BESS is given in table 3.

Table 3: Summary of battery capacity Calculation (night peak)

Description	Value
$P_{shave\,(kW)}$	120
Battery type	lead-acid
Battery lifetime	5
$B_{pwr\,(kW)}$	41.71
Discharged Energy (kWh)	166.84
Battery Capacity (kWh)	238.34
Number of battery units	100
Rated Capacity (kWh)	240

The cost of battery integrated solar PV system which has been calculated using equations (7) and (11) is one hundred and eleeven (111) Million LKR. The unit cost of the energy of solar PV is Rs. 15.12. The cost of grid energy is given in the table 4.

Table 4: Cost of energy of the grid

Time Intervals	Energy cost
Peak (18:30-22:30)	22.50
Day (5:30-18:30)	20.7
Off peak	14.35

After calculating the energy cost of solar PV and BESS power dispatch among the sources of energy has been determined based on flow chart shown in figure 2. Graphical representation of the results is given in figure 4.

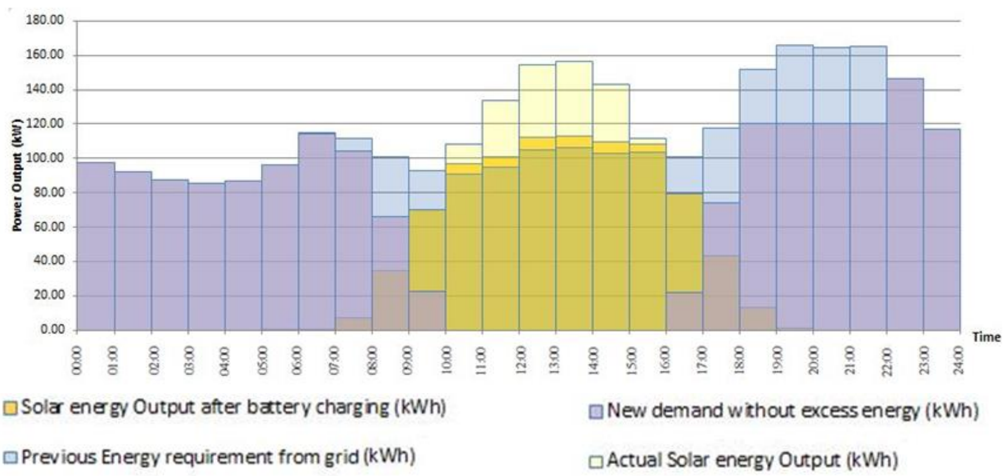

Fig.4 Power dispatch between sources of energy during a day

The cost for energy per day of the proposed model is given in tables 5.

Table 5: Energy Cost of Integrated system

Description	**Cost per day in rupees**
grid energy	33327.37
cost of solar PV+ BESS system	15180.72
Total	**48507.49**

When the energy is purchased only form the gird, the total cost for energy is Rs. 54908.54. The cost breakdown is shown in table 6.

Table 6: Cost for grid energy

Time Interval (hrs.)	**Energy demand (kWh)**	**Cost (LKR)**	**Cost for energy (LKR)**
0530-1800	1288.88	20.70	26679.74
1800-2230	719.99	22.50	18359.78
2230-0530	687.74	14.35	9869.07
Total cost for energy			54908.54

The annual cost saving after installing solar PV system is LKR 7,877196.40. Since there is a capital investment of 111 million rupees for installation and maintenance of solar PV system including BESS, the payback period is around 14 years. Since the lifetime of the proposed system is taken as 20 years the rest six years the total benefit is around 48 million rupees.

V. Conclusion

The results of this study show that in long term the use of solar PV at the distribution level has an economic benefit. Integration of battery energy storage system can reduce the cost for energy during night peak. The maximum benefit of the use of solar PV can be determined by varying the solar PV capacity.

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