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Probabilistic Sizing of Islanded Microgrid Considering Temperature Effect on PV Array

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***Abstract*—The energy efficient microgrid (MG) plays a vital role in electrifying the remote community. But the over/under sized MG resulted in high-cost or unreliable electricity. So, the optimal sizing of MG is implemented in this paper by identifying the optimal control strategy for the highly reliable solar PV/Battery/Diesel generator-based configuration. The negative impact of temperature on the performance of PV array is included in optimal sizing and the resulted changes in the capacity of MG components are estimated and presented. Also, the uncertainty of the design parameters is included in optimal sizing through the probabilistic approach and the distribution of optimal sizes for each MG components are presented to identify the size which provides highest reliability for sensitive applications. It is proved that additional 11% PV array capacity is required to compensate the power loss due to temperature effect but with the advantage of reduction in battery and converter size.**

***Keywords*—Control strategy, microgrid, optimal sizing, photovoltaic system, probabilistic approach.**

I. Introduction

The last-mile connectivity problem remains a challenge for the developing countries [1-2]. Though the existing microgrids (MGs) are unable to provide cheaper electricity than the grid supply, the highest reliability and quality drives the growth of microgrids in developing countries [3-6]. But the poor planning strategy resulted in failure of the MGs within short span. The oversized system fails to offer cheap electricity and the under sized system fails to provide reliable supply which doesn't allow the local growth. The poor planning resulted in poor motivation among the MG investors [7]. So, the optimal sizing is a critical demand among the investors for optimal business gain through high public satisfaction as the last mile infrastructure with highest reliability is far from the reach for the remote communities [8]. So, considering the critical requirement of optimal sizing [9], freely available renewable resources and the reliability requirement, the optimal sizing is performed in this paper for the solar PV/Battery/DG based islanded MG. Due to the dependency of optimal sizing on the control strategies, design variables and the operating environment, the initial analysis is focused on the selection of best control strategy for the Solar PV/Battery/ Diesel generator (DG) based MG. The control strategy is critical in optimal sizing as it decides the priority of the component [10]. The load following (LF), cycle charging (CC) and the combined dispatch (CD) are the different control strategies considered for this analysis [11]. The best control strategy which utilizes more renewable energy at low cost of energy (COE), CO_2 emission and unmet load percentage (ULP) is identified and utilized in optimal sizing of solar PV/Battery/DG based MG. Considering the locally available renewable resources and the components of MG, the solar irradiation (G), temperature (T) and the load demand (L) are identified as design variables. The effect of operating environment in optimal sizing is analysed by including the effect of temperature on the performance of PV array [12]. The resulted changes in the optimal sizes of the components are estimated to show the practical necessity of additional PV modules to compensate the power loss at higher operating temperatures of the PV cell. Initially, the optimal sizing is performed using the deterministic approach with single year and average values of multi-year data. Due to the seasonal variations of the design variables and the related uncertainties the deterministic approach might not yield an optimal solution, hence statistical distribution of the design variables is considered [13-16] and implemented in optimal sizing through the probabilistic approach [17-18]. The suitable probability density function (PDF) [19] is identified and used for generating the samples of each design variable. To guide the investors in planning strategy, the distribution of optimal sizes of each component are presented as normally distributed PDF for the system sized with and without the temperature effect.

The main contributions of this paper are (i) the proposal of an optimal control strategy for the solar PV/Battery/DG based MG; (ii) the analysis of the effect of temperature on the performance of PV array and consequently on the variation in the optimal sizes of MG components; (iii) the inclusion of the uncertainty of the deign parameters in optimal sizing of MG components through probabilistic approach.

The rest of the paper is organized as follows. Section II presents the brief overview of microgrid and the renewable energy resources. Section III presents the proposed methodology and section IV presents the simulation results and discussions. Finally, the section V presents the conclusion.

II. Microgrid And Resources

A. *Microgrid Structure*

In this section the microgrid model used to optimally size the isolated MG is presented. The main objective here is to design a MG which will meet the demand of a rural population with higher reliability, reduced emission, and lower cost by considering the temperature effect on the performance of PV array and the uncertainty of the design variables. The Palari Village from the state of Chhattisgarh in India and the corresponding load profile of this rural population [20] are used in this study. The details of the Village are given in Table I. The different type of consumers and their electricity demand are given in Table II. Though, different software tools exist for MG design and analysis, the HOMER Professional Microgrid Analysis Tool HOMER Pro 3.14.4 is used here considering its advanced features for microgrid design in grid connected and islanded mode [21-22]. The AC microgrid with solar PV array, battery and disel generator (DG) is considered in the analysis. The DG is included in the structure of the MG considering the reliability requirement of the remote villages with no grid access. In the MG structure, the AC load and the diesel generator are connected to the AC bus as shown in the Fig. 1. The solar PV arrray and the battery bank are connected to the DC bus. The power converter which is used to convert the DC output of PV array and battery into AC output at the AC bus depends on the load demand. If there is an exess in electricity

TABLE I
STUDY AREA AND THE LOAD ASSESSMENT

Particulars	Details
Village Name	Palari
District	Bastar
State	Chhattisgarh
Country	India
Latitude	19°635'N
Longitude	81°672'E
Elevation (m)	587
No. of Households	304
Total Population	1624
Primary School	1
Primary Health Subcentre	1
Post office	1

TABLE II
ELECTRICITY DEMAND OF PALARI VILLAGE

Sl. No.	Load types	Daily Demand (kWh/day)
1.	Domestic load, medical centre, and school	222
2.	Shops, community centre, manufacturing unit and streetlights	212
3	Agricultural load	58.6
	Total demand	492.6

generated by the DG, the converter helps to store the excess energy into battery by converting the AC power to DC power. For the cost analysis, the Net present cost (NPC) and the cost of energy (COE) of the islanded MG system are considered.

B. Resources

The general flat plate type PV module is considered with 80% derating factor and 20 years lifetime. The cost component which includes the capital, replacement, operation, and maintenance cost of the PV system is adopted from [20]. The generic 1 kWh Lead Acid batteries with the lifetime of 5 years and the minimum state of charge of 30% are used in the analysis. The cost component of the batteries is taken from [20] and it includes the capital, replacement, operation, and maintenance cost. For the DG usage in India, the cost of fuel, capital, replacement, operation, and maintenance are estimated as 1.1$/L, 500 $/kW, 500 $/kW and 0.03 $/kW/h respectively. Similarly a converter with 15 years lifetime and 96% efficiency is considered with the capital and replacement cost of 154 $/kW each. The data

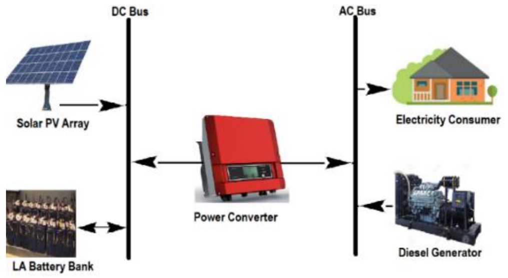

Fig. 1. Components of microgrid

which includes solar irradiation (G) and temperature (T) for the analysis of MG is taken from NASA POWER [23] based on the exact latitude and the longitude of the Palari Village.

III. PROPOSED METHODOLOGY

A. Control Strategy

Initially, to identify the efficient control strategy, the optimal sizing of solar PV/Battery/DG based MG is estimated using the three different control strategies namely, LF, CC and CD. The control strategies which are used to control the power flow among the different components of MG are given in Table III. In all the three control strategies, the power flow is the same for the first two conditions. When the power generated by the PV array (P_{PV}) is equal to the load power demand (P_L), the P_{PV} is fully utilized by the load. If the P_{PV} is larger than the P_L, the P_{PV} is used to supply the load and the excess power will be used to charge the batteries. But when the P_{PV} is smaller than $P_{L,}$ there are two sub conditions and the priority of the component usage is differed among the control strategies.

For the first sub condition in the LF strategy, i.e., when the state of charge (SOC) is equal to the minimum required SOC (SOC_{min}) of the battery, the DG is used only to supply the load and PV array is used to supply the battery. In CC strategy, the DG is running at its optimal capacity to supply the load demand and charges the battery with its excess generation. In the CD strategy, the economic decision is made based on the cost of either operating the DG only to meet the load demand or operating the DG at its optimal capacity to meet the load demand and charging the battery with excess power. The cost of discharging the battery, the cost of operating the DG only to meet the load demand, and the cost of operating the DG at its optimal capacity to meet the load demand as well as to charge the battery are calculated from the equations available in [10].

Similarly, for the second condition i.e., when the SOC is greater than the SOC_{min} of the battery, the economic decision is made either to discharge the battery or operate the DG to meet the load demand based on the associated cost in the LF strategy. In CC strategy, either the battery is used to supply the load, or the DG is operated at its optimal capacity to supply the load and charge the battery based on the economy. In CD strategy, the economic decision is made by comparing the cost of using the battery to supply the load with the cost of operating the DG either to supply only the load or to supply the load and battery. The better control strategy which utilizes more renewable energy from solar PV/Battery/DG configuration at low cost of energy, emission, and unmet load percentage is identified and used for optimal sizing of MG.

TABLE III
DIFFERENT CONTROL STRATEGIES

Condition	Load Following (LF)	Cycle Charging (CC)	Combined Dispatch (CD)
$P_{PV} = P_L$	PV to load	PV to load	PV to load
$P_{PV} > P_L$	PV to (load + excess to battery)	PV to (load + excess to battery)	PV to (load + excess to battery)
$P_{PV} < P_L$ *(i)* $SOC = SOC_{min}$	DG to load & PV to battery	DG to (load + excess to battery)	Based on economy: DG to (load + excess to battery)/ (DG to load & PV to battery)
(ii) $SOC > SOC_{min}$	Based on economy: Battery to load/DG to load	Based on economy: Batt to load/ DG to (load + excess to Batt)	Based on economy: Batt to load/ DG to (load + excess to Batt)/ DG to (load & PV to batt)

B. Deterministic Approach

The optimal sizing of MG is performed using the HOMER Pro tool for the Palari Village. The location specific hourly solar irradiation and temperature of the year 2015 are imported from NASA POWER. The 24-hour hourly load demand of the village is considered for the entire year. To analyze the impact of the temperature on the performance of PV array, the optimal sizing is repeated for two different cases. In case I, the optimal sizing is performed without including the effect of temperature on PV array and in case II the effect of temperature is included. Considering the randomness of *G*, *T* and *L*, the optimal sizing is repeated with the multi-year metrological data. The hourly values of *G* and *T* from 2014-2020 are used to find the average values for each hour of the year. The simulation was repeated with multi-year data, and the resulted sizes are compared with the optimal sizes estimated using the single year data.

C. Probabilistic Approach

Due to the seasonal variation of the *G*, *T* and *L* in different years, the probabilistic approach is considered in this paper to estimate the optimal sizes of MG components with the aim of maintaining higher reliability under uncertainty. In the probabilistic approach, the multi-year data (2014-2020) is used to find the distribution of hourly values of *G* and *T*. The distribution of the multi-year data is modelled as normally distributed PDF. The variation of *L* is considered by the normally distributed $\pm$20% variation of hourly load values. So, the hourly value is considered as mean value and it's 6.66% value is considered as the standard deviation. The simulation is repeated for case I and II with the different hourly samples taken from the normally distributed *G*, *T* and *L* values. The resulted distribution of optimal sizes of the components from case I and II are compared to show the required changes in the optimal sizes of MG components to maintain the reliability for sensitive applications with the practical temperature effect.

IV. RESULTS AND DISCUSSIONS

A. Control Strategy and Deterministic Approach

Initially, the optimal sizing of the isolated MG is performed through HOMER Pro simulation tool for the Palari village. The different loads considered for the village are included in the simulation tool with the average energy demand of 492.6 kWh/day and the peak power demand of 37 kW. For the deterministic approach, the metrological data/design parameters like solar irradiation (*G*) and temperature (*T*) are taken from the year 2015. The hourly values of *G* and *T* are used along with the hourly values of load (*L*) available for a day. The hourly load of a day is used for all the days of the year. The optimal sizes of the MG components are estimated with the 2015-year data and given in Table IV using the three control strategies defined above, to select the best one which controls the power flow for the effective utilization of the PV/Battery/DG based MG components. The resulted optimal sizes under LF and CD control strategies show small variation in PV array, battery, and converter capacity while the resulted optimal sizes under CC strategy show more variation in component sizes. The optimal PV array capacity is reduced from 102 to 93 (9%) and the battery capacity is increased from 528 to 616 (17%) in CC strategy compared to the LF strategy. Similarly, there is a large variation between the optimal sizes estimated using CC and CD strategy. So, the economic and the environmental parameters like COE, ULP, RE (renewable energy) fraction and CO_2 emission are estimated and given in Table V to pick the control strategy which has higher renewable energy utilization, reliability, low emission, and energy price. The CC strategy fails due to lower renewable energy utilization (77.4%) and higher COE, CO_2 emission. Among the remaining LF and CD strategy, the LF strategy is better due to low COE, ULP and higher renewable energy fraction. So, in this paper the LF control strategy is used for the optimal sizing of PV/Battery/DG configuration.

TABLE IV

Control strategy	PV Array (kW)	No. of LA (1kWh) Batteries	Converter (kW)	DG (kW)
LF	102	528	50	45
CC	93	616	45	45
CD	104	568	47	45

OPTIMAL SIZE OF MG COMPONENTS WITH DIFFERENT CONTROL STRATEGIES

TABLE V
ECONOMIC AND ENVIRONMENTAL INDICATORS WITH DIFFERENT CONTROL STRATEGIES

This research is supported by the EPSRC-India collaborative project JUICE (Grant no: EP/P003605/1)

Control strategy	Cost of Energy ($)	Unmet load (%)	Renewable Energy Fraction (%)	CO_2 Emission (kg/yr.)
LF	0.36	1.8E-16	85.1	26,645
CC	0.38	6.95E-17	77.4	32,159
CD	0.37	4E-16	82.6	25,479

The optimal sizing of the MG components estimated using the deterministic approach with the LF strategy is given in

TABLE VI

OPTIMAL SIZES OF MG COMPONENTS THROUGH DETERMINISTIC APPROACH

Control strategy	Parameters	PV Array (kW)		No. of LA (1kWh) Batteries		Converter (kW)		DG (kW)	
	T(°C) & *G* (W/m^2)	Without Temp Eff.	With Temp Eff.	Without Temp Eff.	With Temp Eff.	Without Temp Eff.	With Temp Eff.	Without Temp Eff.	With Temp Eff.
LF	Actual (2015)	102	115	528	520	50	52	45	45
	7 yrs. Avg.	106	116	528	528	45	45	45	45

TABLE VII

OPTIMAL SIZES OF MG COMPONENTS THROUGH PROBABILISTIC APPROACH

position	PV Array (kW)		No. of LA (1kWh) Batteries		Converter (kW)		DG Size (kW)
	Without Temp. Eff.	With Temp. Eff.	Without Temp. Eff.	With Temp. Eff.	Without Temp. Eff.	With Temp. Eff.	
	With DG	With DG	With DG	With DG	With DG	With DG	
μ	110	122	562	535	54	53	54
3σ	101-119	117-127	518-606	518-553	51-58	48-58	50-58

Table VI for two different cases. In case I, the optimal sizing is performed without considering the effect of temperature on the performance of PV array. But in case II, the practical effect of temperature rise on the PV cell is considered and the simulation is repeated for both cases. The resulted optimal sizes with the LF control strategy show that in case II, the PV array capacity is increased from 102 to 115 (13%) to compensate the power loss during the continuous operation of the PV module under the sun and the resulted temperature rise in PV cell. The required battery capacity is reduced though, from 528 to 520 (1.5%), due to the additional PV Modules and their added generation capacity during the low temperature hours. Similarly, the converter size is increased from 50 to 52 (4%). The DG size remain the same in both cases. The variation in the required optimal capacity of the PV module and the battery clearly demonstrates that the temperature effect should be included in the optimal sizing. Due to the uncertainty of the metrological data, the optimal sizing of MG is repeated using the metrological data from different years. The optimal sizes estimated using the data from different years resulted in different sizes and unmet load. So, considering the randomness of *G* and *T*, the multiple-year hourly data (from 2014-2020) is collected for the same location, 8760 hourly average values are estimated for *G* and *T* and used in the simulation. The resulted optimal sizes of the components are given in the second row of Table VI. The resulted optimal size for PV array changed very little, from 102 to 106 and 115 to 116 in case I and case II, respectively. There is no change in the battery size in both cases. In Case II, the resulted optimal size of the converter is reduced from 52 to 45 (13.5%) with the average hourly values of *G* and *T* form multiple years. There is no difference in generator size in both the cases. The resulted DG size is 45 kW in the system which is sized with and without temperature effect using either the single year or multi-year data. It could be concluded that using average hourly values for several years instead of a single year does not have a major effect on size of MG components, a part form slight (13.5%) reduction in the optimal size of converter.

B. *Probabilistic Approach*

To include the uncertainty due to the seasonal variation of solar irradiation, temperature, and the daily change in load, the probabilistic approach is considered and implemented for the PV/Battery/DG based MG using the LF strategy. In the probabilistic approach, the distribution of the hourly *G*, *T* and *L* values (instead of hourly averages) from multi-year data are modelled as normally distributed probability density function. So, 8760 PDFs are generated for each variable and the hourly samples are taken from the same for each simulation. The simulation is repeated for 150 times for each case and the results are presented using PDFs. The distribution of optimal sizes of each MG components are presented in Table VII in terms of the mean and the ±3σ values. The mean value of optimal PV array capacity is increased from 110 to 122 (11%) when the effect of temperature is included in optimal sizing. But the mean value of the required battery capacity is reduced from 562 to 535 (5%) due to the higher generation capacity of additional PV modules at lower temperature conditions. Also, there is a 2% reduction in the converter size in case II. There is no difference in generator size in case I and II. The +3σ values which indicates the 99.73% probable data capture, indicates the size which maintains ~100% reliability. The distribution of optimal sizes of different components are given in Fig. 2. In each graph, there are two PDFs representing the distribution of sizes from case I and case II. In Fig. 2 (a), the PDF of case II is shifted to the right with additional requirement of 8 kW PV array capacity at +3σ to ensure higher reliability with uncertainty. In Fig. 2 (b) the distribution of required battery capacity with multi-year data lies within -3σ and mean value of that obtained without inclusion of temperature effect. In Fig. 2 (c), there is a difference in the mean value and the distribution. But the +3σ value is the same in both the cases. Similarly, there is not much difference in the distribution of optimal DG size as shown in Fig. 2. (d).

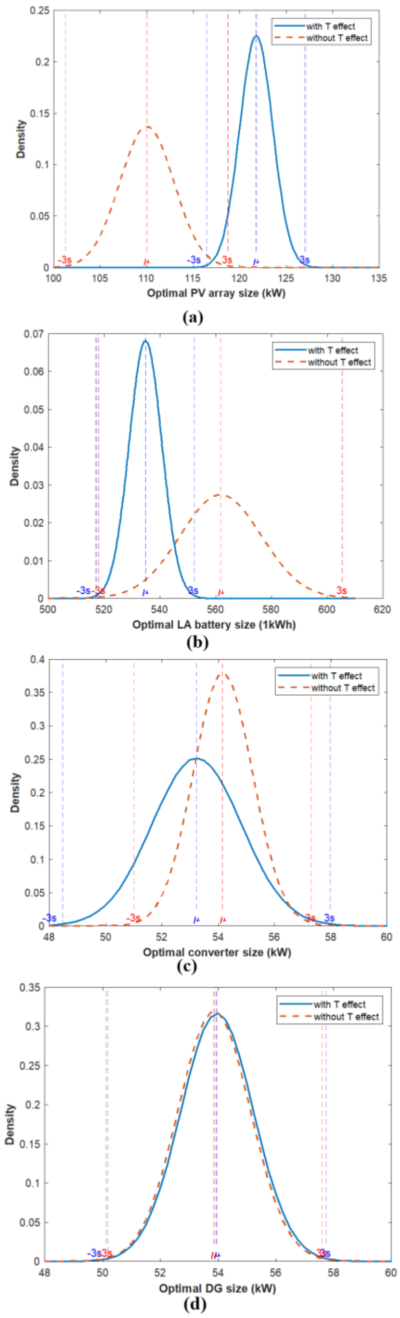

Fig. 2. (a) Distribution of optimal PV array capacity (b) distribution of optimal battery size (c) distribution of optimal converter size (d) distribution of optimal DG size

This analysis shows that the load following control strategy offer better power flow control with maximum renewable energy utilization, low cost of energy, CO_2 emission and unmet load in solar PV/Battery/DG configuration. Also, the necessity of including the effect of temperature on the performance of PV module in optimal sizing to maintain the reliability is proved through the results. The resulted distribution of optimal sizes of MG components using the probabilistic approach demonstrates additional flexibility in development of planning strategy under uncertainty.

V. Conclusion

The planning strategy for the optimal sizing of components of isolated remote microgrid is presented in this paper. Among the different control strategies, the load following control strategy is proved as the best one to utilize the maximum renewable energy in solar PV/Battery/DG based MG at low COE. Also, the required changes in the capacities of MG components under the negative effect of temperature rise on the performance of PV module are presented. The variation in required PV array capacity, battery capacity and converter size due to the PV module's ability to generate more from the low temperature daylight in different case studies and control strategies considered, demonstrated and sometimes opposite dependance of optimal design on input parameter uncertainties and temperature effects. The inclusion of the uncertainties of the design parameters in optimal sizing using the probabilistic approach is therefore necessary to account appropriately for associated uncertainties. The probabilistic approach resulted in distribution of the optimal sizes of each component to ensure the highest reliability of supply. The probabilistic analysis, in addition to offering greater flexibility in optimal sizing of isolated MG components, demonstrated that the inclusion of temperature effect would lead to 11% increase in average size of PV array and consequential reduction of 5% and 2% in battery and converter size, respectively.

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