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STRATEGIC DEPLOYMENT OF LOW-CARBON MICROGRIDS CONSIDERING CARBON POLICIES AND GREEN CITY GOALS

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ABSTRACT

In this paper, a new optimization framework is developed for optimal planning of low-carbon microgrids for clean city applications. It models the effect of recent carbon policies imposed by the environmental protection agencies on the power distribution utilities especially, in urban areas. To mimic the various techno-economic and social aspects of emerging dispatchable distributed generation technologies in the proposed framework, a new objective function is introduced. The moth search optimization technique is adopted to solve the problem aiming to determine the optimal mix of energy generation. Different scenarios are framed and investigated on a benchmark test distribution system of 33 buses. The simulation results are found to be inspiring in quantifying the optimal carbon cap/tax, whilst improving the system performance.

Keywords: Carbon tax, dispatchable generation, distributed energy resources, carbon emission reduction, green city, optimization

1. INTRODUCTION

The growing urban population, energy demand, greenhouse gas (GHG) emission, limited infrastructure have led to the concept of sustainable urban development. The ecological development of modern cities is now assumed by many regulators to be a win-win proposition and numerous initiatives on the "greening of cities" are taking shape across the world [1]. The modern cities are found to be the major consumers of natural energy resources, which may include electricity, diesel/petrol, gases, water, and so on while emitting greenhouse gases into the environment. Therefore, the aim of such development is to provide clean air and water, minimizing the use of land, energy and materials, running a low risk of major infectious disease outbreaks, being resilient to natural disasters, encouraging green behavior, and having a relatively small ecological impact [2, 3]. The global goal of green cities development may target at minimizing the GHG emission produced from various industries.

The traditional power industry is one of the biggest culprits among causes responsible for GHG emission. Therefore, many environmental protection agencies and regulators are making regulations to limit/cap the carbon emitted from the power industry [4, 5]. Moreover, the recent advancements in small or medium-sized power generation and clean renewable power generation technologies have led to the large-scale integration of distributed energy resources (DERs), distributed generation (DG) and microgrids in power distribution systems. The paradigm shift of the modern power industry has established a strong link between green and smart city development and renewable energy sources [6]. This can be found in a European green city index report considering the factors such as CO_2 emission and strategy to reduce it, air quality, and percentage of renewable share in current power generation [7]. Therefore, it is essential to link these aspects and investigate current microgrid planning practices by determining the optimal mix of various DG technologies considering environmental protection policies.

In literature, various active distribution and microgrid planning models have been adopted to maximize the techno-economic and social benefits. However, the effect of the latest emission policies imposed on DNOs is not much explored for the planning and operation of microgrids. The increasing global pressure from environmental protection agencies to reduce GHG emission has also modified the DG integration policies and modern city development [4, 5].

In this paper, an optimization framework is developed for the optimal deployment of low-carbon microgrids,

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considering recently introduced carbon policies for DNOs, in order to match with the green city deployment goals. To achieve this, in Section 2, a comprehensive objective function is proposed considering techno-economic and social aspects of diversified dispatchable DG technologies over multiple load levels. In a social aspect, recent environmental protection policies that already been imposed or will be enforced on DNO activities, based on CO_2 emission produced from DNO activities and different DG technologies, are considered. The proposed model is implemented on a standard 33-bus distribution system and a moth search optimization technique is used to solve it. The simulation results are found to be inspiring as detailed in Section 3.

2. PROPOSED OPTIMISATION FRAMEWORK FOR OPTIMAL DESIGN OF LOW-CARBON MICROGRIDS

In this section, the problem of an optimal planning of low-carbon microgrid and management is formulated.

2.1 Local objectives of DNOs

In practice, DNOs are required to meet multiple objectives during system planning and operations. These can be the minimization of power loss, the reduction in costs of grid energy transactions, annual investments, operation and maintenance requirements, node voltage deviation, asset overloading. Some of these objectives are considered in the proposed model, as discussed in the following sections.

2.1.1 Cost of annual energy purchase from the main grid: The cost of annual energy purchase is considered as one of the objectives while determining the optimal mix of different DGs, expressed as:

$$\min F_1 = \sum_{l\in L} c_l^e.n_l^h.p_l^{grid} \tag{1}$$

where, c_l^e, n_l^h, p_l^{grid}, and L represent the grid energy price ($/kWh), the number of hours, and power purchased (kW) at load level $l \in L$ respectively.

2.1.2 Cost of annualized DG investment and operations: In order to determine the cost-effective optimal mix of different DER technologies, the cost of various annual investments in DGs is also minimized, expressed as:

$$\min F_2 = \underbrace{\sum_{t\in n_{type}} c_t^i.p_t^i.T_d^{-1}.(1+r_{\text{int}})^{T_d}}_{\text{Investment cost of DGs}} + \underbrace{\sum_{t\in n_{type}}\sum_{l\in L} c_t^o.n_l^h.CF_t.p_{l,t}^o}_{\text{O\&M cost of DGs}} \tag{2}$$

where, c_t^i, c_t^o, p_t^i, $p_{l,t}^o$ and CF_t denote the cost of investment ($/kW), operation ($/kWh), deployed capacity (kW), power generation (kW) at load level $l \in L$ and capacity factor of t-type DG respectively. T_d and r_{int} represent the planning duration in years and annual interest rate respectively.

2.1.3 Node voltage profile: Node voltage deviation of the system is one of the measures to identify the voltage profiles across the system. The minimization of node voltage deviation from nominal value, i.e., unity, is considered as one of the DNO objectives, expressed as

$$\min F_3 = \max\left\langle \left|1 - v_{li}\right| \right\rangle \quad \forall l, i \tag{3}$$

here, v_{li} is the per-unit magnitude of node voltage, at node i, at load level l.

2.2 Global Green City Objective

As discussed, one of the global goal of greener cities development is to reduce the GHG emission largely produced from three economic sectors - electricity, transportation and manufacturing industry. Among these gases, CO_2 is at the highest level with more than 50% share, which is being produced from fossil-fuels and various industry processes. Therefore, governments are trying to reduce the global CO_2 emission by imposing CO_2 taxes or cap-and-trade mechanisms on DNOs for polluting the environment by various DNO activities. Generally, carbon taxes would apply not to DNOs but to the bulk power generators supplying power via these DNOs. However, estimating the effect of CO_2 taxes on energy price would be difficult, and require a model far beyond what is done here. Instead, a rough approximation of this effect is used as proposed in [8].

Therefore, in this paper, per ton carbon tax is considered for microgrid and the main grid. The total annual carbon tax paid by the microgrid can be express as:

$$\min F_4 = \underbrace{\sum_{l\in L} c^{tax}.E^{grid}.n_l^h.p_l^{grid}}_{\text{Emission tax on grid energy}} + \underbrace{\sum_{l\in L}\sum_{t\in n_{type}} c^{tax}.E_t^{dg}.n_l^h.CF_t.p_{l,t}^o}_{\text{Emission tax on DG energy}} \tag{4}$$

where, c^{tax}, E^{grid}, and E_t^{dg} represent the carbon tax ($/g), carbon emission in grid and DG energy (g/kWh) respectively.

2.3 Combined objective function for optimal planning of low carbon microgrid

The objective functions expressed in (1), (2) and (4) represent the costs whereas (3) is the technical performance measurement of the system. Therefore, a penalty function based approach is adopted to design a combined objective function. The objective function F_3

expressed in (3) is considered as a penalty function and a combined microgrid design function is expressed below.

$$\min F = \left(F_1 + F_2 + F_4\right) * \left(1 + F_3\right) \tag{5}$$

s. t.

$$p_{il} = v_{il} \sum_{j \in N} v_{jl} Y_{ij} \cos(\theta_{ij} + \delta_{jl} - \delta_{il}) \quad \forall i, l \tag{6}$$

$$q_{il} = -v_{il} \sum_{j \in N} v_{jl} Y_{ij} \sin(\theta_{ij} + \delta_{jl} - \delta_{il}) \quad \forall i, l \tag{7}$$

$$p_t^i \le p_{\max}^{dg} \quad \forall i, t \tag{8}$$

$$\sum_{t \in n_{type}} p_t^i \le p_{peak}^d \tag{9}$$

$$i_{lk} \le i_{Max,k} \quad \forall l, k \tag{10}$$

$$a_{co2}^{cal} \le a_{Max,co2}^{regulator} \tag{11}$$

Equations (6)–(11) express the nodal real power balance, reactive power balance, node voltages, DG penetration level at a node, total DG penetration in the system, branch current, and regulated emission limits constraints respectively; where, p_{il}, q_{il}, δ_{il} represent the real and reactive power injection, and voltage angle of node i at level $l \in L$. $p_{\max}^{dg}$, p_{peak}^{d}, i_{ik}, $i_{Max,k}$, a_{co2}^{cal}, $a_{\text{Max,co2}}^{regulator}$ denote maximum allowed capacity of type t DG at a node, peak demand of system, present and maximum allowed current in feeder k, calculated average emission per kWh, allowed per kWh emission by the regulatory respectively.

3. SIMULATION RESULTS

To demonstrate the effectiveness of this proposed optimization framework, for strategic microgrid planning to achieve green city goals, a benchmark 33-bus test distribution system [9] is considered. It is a 12 kV radial distribution system with total nominal real and reactive power demand of 3.715 kW and 2.300 kVAr respectively. For simplicity, annual load demand is divided into three load levels ($L = 3$), namely light load (50% of nominal for 2000 hrs.), nominal load (for 5260 hours) and peak load (160% of nominal load for 1500 hrs.) as in [10]. The life of DGs and planning duration, T_d = 20 years, annual rate of interest, r_{int} = 12.5%, CO_2 emission from conventional main grid, E^{grid} = 910 kg/MWh and CO_2 tax, c^{tax} = 10$/ton [8]. The grid energy prices of different load levels are referred from [10]. The maximum allowed average CO_2 emission intensity, $a_{Max,co2}^{regulator}$ = 459g/kWh [4]. The goal of this work is to investigate the effect of carbon policies imposed on microgrid planning and operation in green city environment; therefore, five typical dispatchable DG technologies are considered with their capacity factors (CF) to make the investigation applicable. They are diesel engine (DE), gas engine (GE), micro-turbine (MT), biomass (BM) and fuel-cell (FC). To investigate the effect of carbon policies through proposed model, the following scenarios are investigated:

Scenario–I: *Microgrid planning model by considering CO2 emission constraint only, proposed in (11), no tax.*
Scenario-II: *Green city microgrid planning model considering carbon tax mechanism (10$/CO2-ton).*
Scenario-III: *Green city microgrid planning model considering carbon tax mechanism (50$/CO2-ton).*
Scenario-IV: *Green city microgrid planning model considering carbon tax mechanism (100$/CO2-ton).*

Now, a newly introduced meta-heuristic optimization technique is used to solve these cases, i.e., moth search optimization [11]. The optimal simulation result obtained for these scenarios are presented in Table I. The table contains the information of determined optimal DG installation sites (nodes), respective sizes, types, and dispatches over all load levels, under various scenarios. The optimal dispatches shown in peak load level are representing the rated DG capacities suggested by the optimization method. The table also presents the annualized profit (M$), annual CO_2 emission and its reduction percentage.

The simulation results of the proposed planning model show that the combined objective of microgrid planning and green city deployment is depending upon the amount of carbon cap/tax to be imposed on DNO activities up to some extent. For example, the CO_2 emission reduction is high from base case to Scenario-II, 61.12%, but after that almost no effect of increasing carbon taxation is observed, by just 0.09%. Whereas, Scenario-I ensures the carbon cap only. In terms of global green city objective, it has been observed that when carbon tax increases, the percentage share of clean and economical DG technologies is increasing with carbon tax from Scenario-II to IV, i.e., BM and MT. Therefore, it may be suggested that the carbon tax considered in Scenario-II is optimal, i.e., 10$/ton. Due to high investment cost, the share of BM is not found in Scenario-II but appeared in Scenarios III and IV because of high emission tax.

On the other hand, the proposed model also improved the system performance in terms of power loss reduction and node voltage profile improvement, over all load levels. The annual profit of DER deployment is also found to be highest in Scenarios II and IV. On the basis of this case study, it may be suggested that Scenario-II is presenting the best share of DG technologies to achieve maximum benefit for DNO and green city goals simultaneously.

4. CONCLUSIONS

The paper presents a new optimization framework, to optimally deploy microgrids under environmental regulatory schemes, to reduce carbon emission produced by various DNO activities. This model is implemented on a benchmark 33-bus distribution system and different test cases are investigated to realize the effect of carbon cap/tax on green city microgrids. The investigation has revealed that up to some extent, the amount of carbon cap/tax to be imposed on DNO and DER integration profit are depending on available DG technologies or vice versa. In future, energy regulators should optimize the amount of carbon cap/tax to be imposed according to the emission reduction goals and their deadlines. Moreover, it can also be extended for solar and wind generations.

Table I Optimal sites, types, sizes of different DG technologies and various system performance parameters

Scenario	Nodes/ LL	Optimal nodes and dispatch (MW)					Power Loss (kW)	V_{min} (p. u.)	V_{max} (p. u.)	Annual profit (M$)	Annual CO_2 emission (Ton)	Annual emission reduction (%)
		DE	**GE**	**MT**	**BM**	**FC**						
Base case	L	-	-	-	-	-	47.07	0.96	1.00	00.00	31118	00.00
	N	-	-	-	-	-	202.67	0.91	1.00			
	P	-	-	-	-	-	575.31	0.85	1.00			
I	Nodes	**28**	**03**	**15**	**-**	**29**	-	-	-	19.40	14602	53.08
	L	0.12	1.43	0.24	-	0.49	12.30	0.99	1.00			
	N	0.37	2.69	0.42	-	1.08	49.33	0.97	1.00			
	P	0.60	4.20	0.60	-	1.08	187.28	0.94	1.00			
II	Nodes	**28**	**03**	**26**	**-**	**29**	-	-	-	22.31	12100	61.12
	L	0.26	1.30	0.43	-	0.49	11.24	0.98	1.00			
	N	0.60	2.38	0.84	-	1.08	43.19	0.97	1.00			
	P	1.20	3.60	1.20	-	1.20	108.91	0.95	1.00			
III	Nodes	**27**	**29**	**19**	**18**	**-**	-	-	-	22.24	12070	61.21
	L	0.20	0.65	1.31	0.22	-	10.53	0.99	1.00			
	N	0.44	1.26	2.61	0.43	-	42.96	0.97	1.00			
	P	0.60	1.80	4.50	0.60	-	135.65	0.95	1.00			
IV	Nodes	**10**	**29**	**19**	**01**	**17**	-	-	-	22.31	12017	61.38
	L	0.34	0.65	0.87	0.41	0.09	9.53	0.99	1.00			
	N	0.55	1.19	1.98	0.79	0.20	45.48	0.97	1.00			
	P	1.20	1.80	3.00	1.20	0.30	109.64	0.95	1.00			

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