Article

Assessment and Integration of Renewable Energy Resources Installations with Reactive Power Compensator in Indian Utility Power System Network

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Abstract: Renewable energy (RE) resource assessment is essential for planners and investors to increase its penetration capacity, and improve social and economic security. Integration of renewable power generations (RPGs) and reactive power compensators (RPCs) offer potential benefits to the existing power system network by providing a prospect for voltage control, reduction in power losses, sustainability, and reliability improvement. There are proven outcomes with these RPGs and RPCs placement in distribution systems. This work proposes a candidature location and sizing of RPGs and RPCs optimally in the Indian utility transmission power system network. The foremost purpose of this integrated operation at multiple nodes is to increase the performance of the power system concerning power loss and voltage deviation reductions, and voltage stability improvement. The loss sensitivity factor (LSF) based particle swarm optimization (PSO) technique is adapted for finding the candidature locations and sizing the RPGs and RPCs under five different configurations. Simulation outcomes display the proposed methodology can lead to extensive performance enhancement in the power system towards the sustainable development of electric energy transactions. Further, renewable resource assessment is carried out to find the viability of the candidature locations. The potential of wind and solar energy resources is assessed widely and suitable tools are used to evaluate the power extraction through RE at these selected locations. The results show that the candidature locations have great potential to evacuate the energy, which can effectively improve the existing power system technically and economically. Additionally, it is attested that the RPGs can also be utilized for power system enhancement.

Keywords: loss sensitivity factor (LSF); particle swarm optimization (PSO); reactive power compensators (RPCs); renewable power generations (RPGs); voltage stability index (VSI)

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1. Introduction

1.1. Background

The need for electricity is increasing globally due to the prompt progression of population and technological developments that influences the environmental pollution conditions [1,2]. Several renewable resources are utilized around the world notably solar, wind, biomass, hydro, and waves due to the fluctuations in oil prices specifically during adverse situations [3,4]. They are also a cost-efficient practice for the electric power sector, specifically hybridization [5]. Generally, renewable resources adopted for RPGs improve the power system parameters both technically and economically.

Moreover, the integrated operation of RPGs and RPCs in the power system evolves copious benefits in terms of both technical and economical [6]. This integrated operation has been vastly discussed in distribution systems by researchers in various aspects. Nevertheless, an attempt in the transmission system has not been demonstrated greatly. It is a known fact that the optimal allocation of RPGs is the recent research activity that could be adopted in both radial and meshed networks [7]. Particularly, meshed systems are used for transmission systems. In the transmission system, power losses primarily hinge on the current flowing over it. The reactive power losses supplied by reactive elements can be minimized by the installation of RPCs [8]. Furthermore, dynamic VAR compensators such as shunt and switchable capacitors, and static VAR compensators can afford fast-acting reactive power support with improved load-bus/node voltage and reduced power losses [9,10]. However, its efficiency is deeply subject to the placement, size, and category of compensators adopted.

The reliability of distribution systems (radial or loop) is not great when compared with the transmission system because high-level penetration may not be possible in the distribution system due to a higher R/X ratio [11,12]. The installation of RPGs in the transmission system avoids the commissioning of new transmission lines for reliable power transactions that leads to economical saving. Additionally, RPG power injection enhances the voltage profile, energy efficiency, and reliability along with the prevention of transmission overloading [13,14]. Further, the proper installation of RPGs in the transmission system minimizes network losses and enhances network performance compared to lower voltage networks. Therefore, the integrated operation of RPGs and RPCs [15–17] has superfluous advantages and capabilities for the targeted transmission system. However, improper positioning and sizing of RPGs and RPCs construct serious issues to the system such as excess power losses and decaying of voltage magnitudes greatly, which may collapse the complete system [8,18]. Hence, it is imperative to apply an optimization algorithm for positioning and sizing of both RPGs and RPCs for the uttering transmission system. Specifically, the countries like India, renewable capacities are intensive in a few states/regions. Therefore, it is crucial to possess expanded transmission capacity for accommodating increased RPGs at selected locations and their evacuation to the load centers. As renewable energy (RE) projects have a small gestation period, it is vital to plan and execute the transmission projects for faster implementation [11]. It also permits a centralized economic optimization and improves the overall system security [19].

1.2. Literature Survey

In line with the above statement, a literature survey has been carried for optimization techniques. The optimization methods such as analytical, numerical programming, metaheuristic, and hybrid techniques were surveyed. From that, it is found that the metaheuristic methods is effective in reducing the comprehensive search space and offer an optimum solution for the RPC and RPG placements. Metaheuristic algorithms are not requiring derivative particulars and utilizing stochastic rules for solving the problem [11,20]. Among the various metaheuristic techniques such as particle swarm optimization (PSO), genetic algorithm (GA), bat algorithm (BA), grey wolf optimizer (GWO), and artificial bee colony algorithm (ABC), PSO is flexible, easy to implement, and programmable. It has many applications in power systems and therefore the optimal positioning and sizing of RPGs and RPCs are proposed using PSO with the target of shrinking power losses and voltage deviation, and enhancing stability in transmission systems [15,21]. In addition to this, the loss sensitivity factor (LSF) is adopted for the optimal location of RPGs and RPCs.

Further, the potential assessment for candidature locations is performed. Therefore, it is an essential task to realize the geographical dispersal of wind and solar potential and their secular output characteristics [22,23]. Additionally, it helps the stockholders and planners to find suitable sites of copious resources with low volatility [24,25]. Notably, the Indian state of Tamilnadu has the maximum installed capacity of grid-integrated renewable power compared with other states particularly 35% of India's installed capacity of wind [26].

Recognizing preeminent quality RE resources can prioritize potential renewable projects based on present transmission infrastructure [27]. Considering all these implications, an extensive review of numerous state-of-the-art literature works related to the optimal siting and sizing of RPGs and RPCs in the transmission and distribution systems is concisely presented in Table 1 for ready reference [11,21,28,29]

Table 1. Summary of recent works related to the optimal installation of renewable power generations (RPGs) and reactive power compensators (RPCs).

Ref. No.	Year	Objective Function	Installations		Test System	Research Gap (Technical Limitations/ Drawbacks)
			RPG	RPC		
[17]	2016	Minimizing total cost	✓	✓	28-bus distribution system	Single test system is considered
[30]	2016	Minimizing power losses	✓	✓	33 and 119-node distribution systems	Economic evaluations are ignored
[31]	2016	Minimizing total cost of losses	✓	✓	33 and 69-bus distribution systems	Investment cost analysis ignored
[32]	2016	Minimizing network power losses and improving the voltage stability	✓		30-bus transmission system	Only solar DG is considered
[15]	2017	Minimizing the real and reactive power losses	✓	✓	33, 69, and 119-bus distribution networks	Voltage stability and economic deliberations are ignored
[6]	2018	Minimizing distribution power losses, power generation costs, and generation units' emissions, and improving voltage profile and voltage stability index	✓	✓	33, 69-bus and Egyptian distribution networks	Reactive power injection from DGs alone ignored
[16]	2018	Optimizing techno-economic objective	✓	✓	33-bus distribution system	Strategies for voltage enhancement are ignored
[33]	2018	Minimizing generation cost, power loss, and voltage deviation	✓	✓	30, 39, and 118-bus test systems	Voltage stability and power factor constraints ignored
[7]	2019	Improving reliability	✓		IEEE Reliability Test System (RTS-79)	Single transmission system is considered
[12]	2019	Minimizing power loss and improve voltage profile	✓	✓	33, 69, and 119-bus distribution networks	Few network constraints are ignored
[34]	2019	Reduction of active, reactive power supply and real power loss, improvement of branch current capacity, voltage profile and voltage stability	✓	✓	51 and 69-node distribution systems	Economic considerations are not considered
[35]	2019	To analyze the impact of integration of renewable sources on the grid			Moroccan transmission grid	Optimal location and size of DGs/CBs are ignored
[36]	2019	Minimizing active power losses	✓		Algerian transmission power system	Only photovoltaic source is considered
[37]	2019	Minimizing active power losses and fast voltage stability index	✓		57-bus transmission system	Only photovoltaic DG is considered

Table 1. Cont.

Ref. No.	Year	Objective Function	Installations		Test System	Research Gap (Technical Limitations/ Drawbacks)
			RPG	RPC		
[38]	2020	Improving transmission security and minimizing DG investment cost	✓		30-bus transmission system	Only wind DG is considered
[29]	2020	Minimizing active and reactive power losses, and total voltage deviation, and improving voltage stability index	✓	✓	33 and Brazil distribution systems	Reactive power injection from DGs ignored
[39]	2020	Minimizing power losses and enhancing voltage profile	✓	✓	69-bus distribution system	DG number is fixed and a single test system is considered
[40]	2020	Minimizing the power losses, power generation costs, and generation units' emissions, and enhance the voltage profile	✓	✓	33-bus distribution system	Voltage stability ignored, only one test system is considered
[41]	2021	Minimizing the cost of energy losses, peak power losses, and the capacitor	✓	✓	24-bus distribution network	Single test system alone is considered
[42]	2021	Minimizing real power losses, power generation costs, emissions, and voltage deviation index, and improving voltage stability index	✓	✓	33 and 69-bus distribution systems	Real-time system is ignored

1.3. Research Gaps

In summary, the following shortfalls can be found in the literature review:

- Most of the previous studies are conducted on distribution systems.
- Assessment of renewable energy potential is not performed together with optimal allocation.
- Positions of RPGs and/or RPCs are fixed in some works.
- Few network constraints are ignored.
- Economic considerations are unnoticed in few articles.
- The results obtained by few methods are suboptimal.

Considering all the above limitations, this article scrutinizes the optimal allocation of RPCs and RPGs associated with the assessment of solar and wind energy potentials. To demonstrate these applications, a part of the Indian Utility Power System (IUPS) namely the Chennai region is considered. Nonetheless, the proposed method of research can be applied to other locations also. The modeling and viability of the system in the proposed locations are assessed through software platforms and the results produced can be used to implement at the field level.

1.4. Objectives

The present analysis of this work aims to achieve the optimal allocation of RPGs/RPCs. Notably, the following objectives are focused

- To determine the optimal locations and sizes of RPGs and RPCs in the IUPS.
- To minimize the power losses and voltage deviation, and maximize voltage stability.
- To realize the technical and economic impacts through the proposed PSO algorithm.
- To study the feasibility of the candidature locations with real-time resource availability.

The above-mentioned objectives are demonstrated using various factors and constraints and the overall contributions are illustrated in Figure 1.

Figure 1. Overview of the proposed study.

1.5. Organization of the Paper

The remainder of this article is structured as follows. Section 2 presents the problem formulation. Subsequently, the optimal location of RPCs and RPGs based on LSF is detailed in Section 3. In Section 4, the concept of the PSO algorithm is illustrated. The description of the IUPS is presented in Section 5, and Sections 6 and 7 present the numerical results and discussions respectively along with cost analysis. Further, the RE potential assessments for candidature locations are presented in Section 8 and lastly, Section 9 concludes the complete work.

2. Problem Formulation

The problem formulation for the optimal placement and sizing of the RPGs and RPCs in the transmission network is a complex practice. This work articulates the procedure to minimize the active power loss and voltage deviation index, and improve the voltage stability index that embraces the power flow solution under two categories (with and without RPGs–RPCs in the transmission system).

The power balance equations are:

$$P_i + P_{Gi} = P_{Di} + P_L, \quad (1)$$

$$Q_i + Q_{ci} = Q_{Di} + Q_L. \quad (2)$$

where, P_i and Q_i are real and reactive power flows at node i , respectively; P_{Di} and Q_{Di} are real and reactive power loads at node i , respectively; P_L and Q_L are real and reactive power losses at node i , respectively; P_{Gi} is active power injected by RPGs at node i ; and Q_{ci} is reactive power injected by RPCs and RPGs at node i .

2.1. Objective Functions

The main three technical objective functions considered are minimization of power losses (M_1), minimization of voltage deviation index (M_2), and maximization of voltage stability index (M_3) as described below.

2.1.1. Minimization of Power Losses

In the transmission network, total line losses are interrelated with the line current. The reduction in line currents can be achieved by properly placing RPGs and RPCs. The objective function for real power loss can be expressed [43,44] using Equation (3)

$$M_1 = \min (P^{\text{loss}}) = \min \left(\sum_{k=1}^{nl} g_k (V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)) \right), \quad (3)$$

where g_k is a conductance of transmission line; V_i and V_j are voltage magnitudes at nodes i and j , respectively; δ_i and δ_j are the phase angles at nodes i and j , respectively; and nl is the number of transmission lines in the network.

2.1.2. Minimization of Voltage Deviation Index

To transmit the power with quality, the effective way is to minimize the voltage deviation index (VDI). It is a measure of the sum of the absolute voltage difference between the nominal voltage (1.0 per unit) and the actual voltage at all the load buses in the system. Minimization of VDI can be calculated as follows [33].

$$M_2 = \min (\text{VDI}) = \min \left(\sum_{i=1}^{N_{PQ}} |V_n - V_i| \right), \quad (4)$$

where N_{PQ} is the total number of load buses; V_n is the nominal voltage; and V_i is the actual voltage at i^{th} node.

2.1.3. Maximization of Voltage Stability Index

Optimal installation of RPGs and RPCs in the transmission network improves the voltage stability index of the network [30] that can be expressed as voltage stability index (VSI).

$$M_3 = \max (\text{VSI}), \quad (5)$$

$$\text{VSI}(t) = \left[|V_i|^4 - 4(P_j X_{ij} - Q_j R_{ij})^2 - 4(P_j R_{ij} + Q_j X_{ij}) |V_i|^2 \right]. \quad (6)$$

where V_i is the voltage at i^{th} node; X_{ij} and R_{ij} are the reactance and resistance of the line between nodes i and j , respectively; and P_j and Q_j are the real and reactive power of load at j^{th} node, respectively. For a stable transmission system with “ n ” number of nodes, $\text{VSI}(t) \geq 0$, for $t = 2, 3, \dots, n$. The objective functions are subjected to the following operating constraints.

2.2. Constraints

The constraints are noteworthy fragments of the optimization process. These constraints are concisely termed as follows.

2.2.1. Power Balance Constraints

The power balance constraint [33,45] is a measure of equality constraint that characterizes the equilibrium of real and reactive power at the i^{th} node as shown in Equations (7) and (8).

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{N_d} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}), \quad (7)$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{N_d} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}). \quad (8)$$

where P_{Gi} and Q_{Gi} are real and reactive powers at the i^{th} node (Injected) respectively; P_{Di} and Q_{Di} are real and reactive powers demanded at the i^{th} node respectively; B_{ij} and G_{ij}

are transfer susceptance and conductance between the i^{th} and j^{th} nodes, respectively; θ_{ij} is voltage angle difference between the i^{th} and j^{th} nodes; and N_d is a total number of nodes.

2.2.2. Voltage Constraints

The voltage constraints [46] are represented as

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}, i = 1 \dots N_{PQ}. \quad (9)$$

where $V_{Li}^{\min}$ and $V_{Li}^{\max}$ are the lowest and highest permissible values of the voltage at the i^{th} node respectively; V_{Li} is RMS value of i^{th} load bus voltage; and N_{PQ} is a total number of load buses.

Further, the IEEE 1547 standard represents voltage regulation limits between the nodes should be within $\pm 5\%$. Hence, $V_{Li}^{\min}$ and $V_{Li}^{\max}$ were assumed to be 0.95 p.u. and 1.05 p.u., respectively [47].

2.2.3. Transmission Line Loading Constraints

For safe and reliable operation of the system, the transmitted power between the nodes must not exceed the rating during steady-state operation and it is represented as follows [48]

$$S_{Li} \leq S_{Li}^{\max}, i = 1, \dots, N_t. \quad (10)$$

where S_{Li} is the actual loading; $S_{Li}^{\max}$ is the maximum loading; and N_t is the total number of transmission lines.

2.2.4. Reactive Power Resources Constraints

The injection and absorption of reactive power are controlled by minimum and maximum limits [33] as given in Equation (11).

$$Q_{Ri}^{\min} \leq Q_{Ri} \leq Q_{Ri}^{\max}, i = 1, \dots, N_R. \quad (11)$$

where Q_{Ri} is reactive power injection at the i^{th} node; N_R is the number of installed reactive power resources; and $Q_{Ri}^{\min}$ and $Q_{Ri}^{\max}$ are a minimum and maximum capacity of reactive power resources respectively.

The rating of the RPCs is set to be 0 and 250 MVAR for safe operation [49].

2.2.5. RPGs Capacity Constraint

The real power generated by all RPG units is limited to the total demand of the network [43].

$$\sum_{i=1}^{N_{RPG}} P_{RPGi} \leq P_D. \quad (12)$$

where P_{RPGi} is active power injected by RPGs at the i^{th} node; P_D is total active power demand; and N_{RPG} is a total number of subunits.

2.2.6. Power Infeed and Power Factor Constraints

During the power injection from the RPG unit, power served from the transmission part may exceed that influence the voltage rise at the point of common coupling on account of reverse power flow. To avoid this scenario, the power infeed into the transmission network should not be negative [50].

$$P(t) \geq 0, \forall t, \quad (13)$$

where $P(t)$ is power infeed at i^{th} node at any time t .

$$0.85 \leq pf_{RPGs} \leq 1. \quad (14)$$

The power factor of RPGs is restricted to the range from 0.85 (lag or lead) to unity.

3. Optimal Location of RPCs and RPGs Based on LSF

3.1. Loss Sensitivity Factor Method

Optimal locations for RPC and RPG installation are determined based on the losses and sensitivity at the nodes of the transmission system using the loss sensitivity factor (LSF) method. Loss sensitivity is denoted as the variation in the losses corresponding to the compensation supplied by locating the RPCs and RPGs. LSF is used to determine the sensitive nodes that are susceptible to further loss reduction when real and reactive power injected by the RPG and RPC units are installed at that location.

LSF is employed in this work to assign the candidate nodes for RPCs and RPGs in the transmission system. The candidate load nodes in the system with no pre-installed generation units would be considered. Consequently, the area of search and time is significantly condensed in the optimization process.

3.2. Identification of Optimal Locations Using the LSF Method

After determining the real power losses for all the nodes from the base case load-flow solution (uncompensated), the LSFs are computed using Equation (15) at each node of the transmission system. Further, it is sorted in descending order for all the transmission lines to form the priority list. The “end nodes” of the transmission lines are considered for sorting the LSF values that can decide the sequence of nodes to be selected for compensation [30].

$$LSF_{ij} = \frac{\partial P_{ij \text{ loss}}}{\partial Q_j} = \frac{2Q_j R_{ij}}{|V_j|^2}, \quad (15)$$

where $P_{ij \text{ loss}}$ is the active power loss in the line between the nodes i and j ; Q_j is total reactive power supplied behind the j^{th} node; R_{ij} is the resistance of line between the i^{th} and j^{th} nodes; and V_j is the voltage magnitude at the j^{th} node. Furthermore, the voltage magnitudes were normalized for all the nodes by assuming the minimum bus voltage as 0.95 using Equation (16). The candidate nodes for RPCs are adopted when the normalized values are less than 1.01 [18,51].

$$\text{Normalized } V_i = V_i/0.95, \quad (16)$$

Based on the normalized magnitudes of voltage and the LSF, the candidate nodes for RPCs and RPGs installations are decided when the normalized voltage values are lower than 1.01. Moreover, RPGs can be exhibited as negative real and reactive power loads, i.e., PQ bus [44,52] and it prevents reverse power flow in the system [32]. The new real and reactive power absorbed (P_{nli} and Q_{nli}) at the i^{th} node after the placement of RPGs was calculated using Equations (17) and (18):

$$P_{nli} = P_d - P_{RPG}, \quad (17)$$

$$Q_{nli} = Q_d - Q_{RPG}. \quad (18)$$

where P_d and Q_d are the real and reactive power demand respectively and P_{RPG} and Q_{RPG} are real and reactive power injections from RPGs respectively.

4. Algorithm

In this proposed work, the PSO algorithm was used to find the optimal position and size of RPCs and RPGs in the targeted system. It is a population-based stochastic optimization method with a simple model and can be easily applied to computer programs. Each particle denotes a candidate for the optimization problem. To achieve the objectives, the initial population is randomly generated by the PSO algorithm that representing the RPC and RPG sizes. Further, the conventional power flow solution is adopted to compute the total power losses and voltages at each node in the targeted system. PSO generates

other dimensions for both RPCs and RPGs until minimum losses are obtained. If it satisfies, then the size and location are considered as the optimum.

The obtained solution dependent on the initial swarm, but prone to the local optimal. To overcome this, parameters of PSO such as swarm size, maximum iteration, weighting factor, and inertial weight are regulated sensibly [44]. However, the main objective of the metaheuristic method is to attain a reduced search space, eluding local optimal solutions and enhancing the overall performance. Based on the values of LSF, search space was formed for optimal locations of RPCs and RPGs. PSO was used for the sizing of both RPCs and RPGs for the targeted system. Equations (19) and (20) were adopted to update the particle's velocity and position during swarm flight.

$$V_i^{t+1} = W^t V_i^t + c_1 r_1 (PBest_i^t - X_i^t) + c_2 r_2 (GBest^t - X_i^t) \quad (19)$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (20)$$

where V_i^{t+1} and V_i^t are the velocity of the i^{th} particle in iteration $t + 1$ and t , respectively; X_i^{t+1} and X_i^t are position vectors of the i^{th} particle in iteration $t + 1$ and t , respectively; r_1 and r_2 are two random numbers in the unit interval; and c_1 and c_2 are two acceleration constants with dissimilar weights to the "pbest" and "gbest".

The inertia weight is updated using the following formulation.

$$W^t = W^t \times (1 - \alpha) \quad (21)$$

where W^t is inertia weight and α is the update coefficient.

The overall organization of the proposed methodology for the optimal placement of RPGs and RPCs is described in the flowchart of Figure 2.

Figure 2. Flowchart of the proposed technique for positioning and sizing of RPGs and RPCs.

5. Description of the IUPS

The IUPS has been adopted to evaluate the effectiveness of the proposed method. A part of the Chennai transmission network, Tamilnadu, India is considered for further analysis. Based on the geography of Chennai city, several nodes, transmission lines, load centers, generating station, etc., has been represented as given in Figure 3. It consists of 19 nodes (5 PV and 14 PQ nodes), which deliver the power to various parts of the cities through 28 transmission lines. The generator, load, and transmission line data of the IUPS are detailed in Appendix A.

Figure 3. Single line diagram of the Indian Utility Power System (IUPS).

The PSO approach and the load-flow solution are carried out using MATPOWER 7.0 package [53] in MATLAB 2018a version on a personal computer with a 1.6 GHz, i5 processor, 64-bit, and 8 GB RAM. It encompasses bidirectional data exchange between MATLAB and MATPOWER.

The parameters of PSO considered for this work are shown below [44,54]:

- Inertia weight (W^t) = 1 (for improved convergence and stability).
- Update coefficient (α) = 0.05 (to speed up the convergence).
- Cognitive and social components (c_1 and c_2) = 2 (to avoid local optima).
- Number of particles = 50 (optimal performance).
- The stopping criterion is set as the maximum number of iterations = 100.

6. Numerical Results

The current performance of the IUPS exhibits poor reactive power management (affect the voltage portfolio), increased power loss, and line loading. Consequently, the integrated operation of RPCs and RPGs is adopted. They are optimally sized and commissioned to minimize the real power loss and voltage deviation, and improve the static voltage stability using the PSO algorithm. In particular, the determination of their optimal sizes is obtained using PSO and the impact of the installation of RPGs and RPCs on various locations is studied using LSF values. To highlight the superiority of the proposed approach, five test scenarios are considered and tabulated in Table 2.

Table 2. Test cases and their configuration.

Cases	CommissioningSizing		RPCs	RPGs	Power Factor	
					Unity	0.85 Lead
Case 1	✓	✓	✓			
Case 2	✓	✓		✓	✓	
Case 3	✓	✓		✓		✓
Case 4	✓	✓	✓	✓	✓	
Case 5	✓	✓	✓	✓		✓

Case 1: Optimal placement and sizing of RPCs

The reactive power losses in the transmission system can be minimized by optimally commissioning the RPCs. The RPCs can be located at the candidate nodes obtained from the LSF method. The overcompensation can be avoided by selecting the size of RPCs lower than the total reactive power loads of the transmission system.

Case 2: Optimal placement and sizing of RPGs at UPF

RPGs working at unity power factor (UPF) inject only real power. Further, the method of LSF is applied to choose the candidate nodes. The total number of RPGs installed is three and the total capacity of RPGs is less than the total real power demands of the transmission system.

Case 3: Optimal placement and sizing of RPGs at LPF

In case 2, the RPGs are allowed to inject only real power. In this case, the RPGs are allowed to inject both real and reactive powers. The total number of RPGs and LSF nodes considered is similar to case 2. The real and reactive power sizing of RPGs are less than the total real and reactive power demands of the transmission systems respectively.

Case 4: Optimal placement and sizing of RPCs and RPGs at UPF

The unified operation of RPGs at UPF and RPCs provides surplus benefits to the transmission system. Both the cases, i.e., case 1 and case 2 are combined. The norms for selecting the candidate nodes and sizing of RPCs and RPGs are the same as stated in cases 1 and 2.

Case 5: Optimal placement and sizing of RPCs and RPGs at LPF

The integrated operation of RPCs and RPGs at LPF provides maximum advantages. It is the combination of two cases case 1 and case 3. The criteria for candidate node selection and capacity of RPCs and RPGs are the same as mentioned in cases 1 and 3.

Furthermore, RPGs are modeled as Type-I generating units (photovoltaic systems, microturbines) that supply real power with unity power factor and Type-III generating units (controllable synchronous generator and biogas plants) deliver both active and reactive power at a prespecified operating power factor of 0.85 (leading) [30]. The total

number of RPGs location is three but there is no improvement in the power losses when the RPGs location is increased. The entire load nodes are considered to be probable candidates for the commission of RPGs and RPCs. Additionally, LSF is utilized to predict the sensitive nodes, which are prone to loss reduction when real and reactive powers are injected by the RPCs and RPGs.

6.1. Case 1

In this fragment, optimal placement and sizing of RPCs are adopted. Figure 4 provides the candidate nodes based on their LSF.

Figure 4. Loss sensitivity factor (LSF) values.

The RPC size was assumed to vary between 0 and 250 MVAR. Consequently, PSO resolved the optimum sizing from the candidate nodes based on the LSF values. It was perceived that the optimum location of RPC was node 13 with a sizing of 193 MVAR. Though, the LSF value was high at node 15; most cooperating results were obtained when a single RPC was placed at node 13 by the proposed algorithm. Further, the real power losses are reduced from 93.185 to 49.78 MW (about 46.58%). Additionally, the voltage deviation index was reduced from 0.0418 to 0.0068 p. u. and the voltage stability index was improved from 0.6467 to 0.9522 respectively as shown in Table 3. The voltage magnitudes of all the nodes are depicted in Figure 5 that displays overall enhancement and accomplished within the band limit.

Table 3. Results for the RPC location.

RPC Size in MVAR (Bus No.)	Power Loss (MW)	Loss Reduction (%)	Average Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated	93.185	0	0.9582	0.0418	0.6467
193 (13)	49.78	46.58	0.9932	0.0068	0.9522

6.2. Case 2

In this case, the optimum sizing and position were adopted based on the LSF similar to above. The maximum sizing of RPGs [11] is subject to the constraint given in Equation (12). However, it is also limited to another constraint, i.e., connected transmission line capacity [55]. Under this condition, the proposed algorithm generated the optimum positioning and sizing and their optimized results are displayed in Table 4. It is noticed that the proposed technique achieves the most cooperating results compared to case 1.

Three RPGs were installed at buses 4, 9, and 11 with penetration of 257.53, 164.72, and 115.17 MW respectively. It reduced the real power loss of about 46.837 MW with reduced VDI and enhanced VSI of 0.0138 and 0.8597 respectively. Further, the average voltage of the system obtained a stable value of 0.9862 p.u. approximately. Moreover, the voltage profiles of different nodes were enhanced as indicated in Figure 6.

Figure 5. Comparison of the voltage profile before and after case 1 configuration.

Table 4. Results for different RPG locations at unity power factor (UPF).

Techniques	RPGs Size in MW (Bus No.)			Total RPG Size (MW)	Power Loss (MW)	Loss Reduction (%)	Average Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated	—			—	93.185	0	0.9582	0.0418	0.6467
PSO	257.53 (4)	164.72 (9)	115.17 (11)	537.42	46.837	49.74	0.9862	0.0138	0.8597

Figure 6. Comparison of voltage profile before and after case 2 configuration.

6.3. Case 3

This fragment reported the numerical results of optimal commissioning and sizing of RPGs at the leading power factor (0.85). RPGs were excluded to inject reactive power to the transmission network in the former study case (Case 2). The proposed algorithm offered

significant active power loss reduction and VDI along with enhanced VSI compared to the previous cases 1 and 2. The sizing of real and reactive power for RPGs, real power losses, average voltage, VDI, and VSI varies as shown in Table 5.

Table 5. RPGs locations at LPF.

RPGs Size in MW + jMVAR (Bus No.)			Total RPG Size (MW) and Power Factor	Power Loss (MW)	Loss Re- duction (%)	Average Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
250.12 + j38.13 (4)	Uncompensated		—	93.185	0	0.9582	0.0418	0.6467
163.66 + j13.97 (9)	1.24 + j196.95 (13)		(415, 0.86)	45.981	50.66	0.9959	0.0041	0.9701

The proposed technique optimized the active power losses enormously from 93.185 to 45.981 MW (50.66% reduction) with total active power penetration of 415 MW at 0.86 p.f. using RPGs. It shows an enriched improvement compared to case 2. Further, the average voltage was also enhanced from the base case to 0.9959 p.u. The value of VDI was reduced from 0.0418 to 0.0041 p.u. and the enhancement of VSI was achieved from 0.6467 to 0.9701 p.u. This consequence improved voltage magnitude in all nodes as shown in Figure 7 particularly in nodes 13 and 15.

Figure 7. Comparison of voltage profile before and after case 3 configuration.

6.4. Case 4

In this part, the combined operation of RPGs and RPC was adopted to improve all three objectives while operating at the unity power factor. The simulation results of the proposed method are summarized in Table 6. It shows that the PSO offers the utmost cooperating results in determining the optimal size and site of RPGs and RPC allocation problem compared with a previous study, i.e., cases 1–3. The proposed method reduced the total active power loss from 93.185 to 44.84 MW (reduction of 51.88%). Additionally, the proposed technique installed three RPGs with penetration of 257.57 MW, 164.65 MW, and 114.91 MW at buses 4, 9, and 11 respectively. The average voltage level was further improved to 0.9969 p. u. compared with earlier cases. Moreover, VDI was minimized and VSI was enhanced from their base value to 0.0031 p.u. and 0.9676 p.u. respectively.

Table 6. Combination of RPC and RPGs at UPF.

RPGs Size in MW (Bus No.)			Total RPG Size (MW)	RPC Size in MVAR (Bus no.)	Power Loss (MW)	Loss Re- duction (%)	Average Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated			–		93.185	0	0.9582	0.0418	0.6467
257.57 (4)	164.65 (9)	114.91 (11)	537.13	194.55 (17)	44.84	51.88	0.9969	0.0031	0.9676

The combination of RPGs and RPC demonstrated amended outcomes recommended by the proposed algorithm. Further, the voltage profile of all the nodes exhibited prodigious magnitudes and located within the band limit as given in Figure 8.

Figure 8. Comparison of voltage profile before and after case 4 configuration.

6.5. Case 5

The specification of this case is similar to case 4 but RPGs with a leading power factor. Therefore, the reactive power component of the RPGs amended the complete system performance in all aspects. The proposed algorithm offered more reduction in the active power loss and VDI along with enhancement of VSI in contrast to the previous cases, i.e., case 1 to case 4. Particularly, the average voltage of the system revealed the influence of RPGs while operating at a leading power factor and is depicted in Table 7. It exemplifies the potential of this configuration with a condensed power loss from 93.185 to 44.48 MW (44.48% reduction). The VDI was reduced from 0.0418 to 0.0013 p.u. and VSI was enhanced from 0.6467 to 0.9748 p.u. for the total RPG size of 524.8 MW at 0.99 p.f. and RPC size of 189.64 MVAR at node 13. The average voltage was also enhanced to 0.9987 p.u. Further, this configuration enhanced the overall system voltage profile as plotted in Figure 9.

Table 7. Integrated operations of RPC and RPGs at 0.85 PF.

RPGs Size in MW + jMVAR (Bus No.)			Total RPG Size (MW) and Power Factor	RPC (MVAR)	Power Loss (MW)	Loss Re- duction (%)	Average Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated			-	-	93.185	0	0.9582	0.0418	0.6467
259.66 + j41.57 (4)	159.21+ j9.73 (9)	105.92 + j27.09 (11)	(524.8, 0.99)	189.64 (13)	44.48	52.27	0.9987	0.0013	0.9748

Figure 9. Comparison of voltage profile before and after case 5 configuration.

7. Comparative Analysis

7.1. Technical Parameters

The optimal positioning and sizing of RPGs and RPC were established for the IUPS. Based on the results obtained with a different configuration, the comparison of outcomes corresponding to the minimization of the loss function, minimization of voltage deviation index, and maximization of voltage stability index are illustrated in Table 8.

Table 8. Summary of test scenarios.

Test Cases	RPC Position Size (MVAR)		RPGs Position Size (MW + jMVAR)		Real Power Loss (MW)	Average Voltage (p. u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated	-	-	-	-	93.185	0.9582	0.0418	0.6467
Case 1	13	193	-	-	49.78	0.9932	0.0068	0.9522
Case 2	-	-	4	257.53 + j0	46.837	0.9862	0.0138	0.8597
			9	164.72 + j0				
			11	115.17 + j0				
Case 3	-	-	4	250.12 + j38.13	45.981	0.9959	0.0041	0.9701
			9	163.66 + j13.97				
			13	1.24 + j196.95				
Case 4	17	194.55	4	257.57 + j0	44.84	0.9969	0.0031	0.9676
			9	164.65 + j0				
			11	114.91 + j0				
Case 5	13	189.64	4	259.66 + j41.57	44.48	0.9987	0.0013	0.9748
			9	159.21 + j9.73				
			11	105.92 + j27.09				

Further, real power losses for each case were compared with an uncompensated system and it was observed that the total real power loss reduction of 44.48 MW (about 52.27%) took place significantly in case 5 compared with other configurations by adopting the optimal positioning of RPGs and RPC (Figure 10a).

Figure 10. Comparative analysis: (a) real power loss; (b) average voltage; (c) voltage deviation index; and (d) voltage stability index.

Additionally, the obtained magnitude of average voltage (p.u.), VDI, and VSI are displayed in Figure 10 that represents the effectiveness of the proposed algorithm in the IUPS. In a nutshell, integrated commissioning and sizing of RPC and RPGs operated at a 0.85 leading power factor reported the comprehensive enhancement in the IUPS using PSO methodology incorporated with LSF. Further, a comparative analysis was performed between bus voltage profiles and power losses for various cases as illustrated in Figures 11 and 12 respectively. It is observed that the optimal allocation of RPC and RPG units working at 0.85 LPF (Case 5) enhanced the voltage profile of the entire network. Moreover, the active power losses were minimized significantly in all the transmission lines for Case 5 (Figure 12). It is also observed from the numerical results and comparative analysis parts that the proposed algorithm could be applied to larger real circuits but with extended computing and running times.

Figure 11. Voltage profiles of various cases of the IUPS.

Figure 12. Power losses at each line for different cases of the IUPS.

7.2. Cost Analysis

Normally, the cost of electric power generated by each RPG and RPC consists of specific components such as capital cost, operation, and maintenance (O & M) cost, and fuel cost [56]. The total electric power generation costs (C) can be determined using the following Equation [6]:

$$C = \sum_{i=1}^{N_{RPG}} (C_{RPGi}) + C_{RPC} + C_{Grid}, \quad (22)$$

where N_{RPG} is the total number of RPG units. The power generation cost for each RPG unit (C_{RPGi}) can be calculated as:

$$C_{RPGi} = a + b \times P_{RPGi}, \quad (23)$$

where P_{RPGi} is the real power capacity of the RPG unit at i^{th} bus, and the coefficients a and b can be calculated as follows:

$$a = \frac{\text{RPG Capital cost (\$/kW)} \times \text{RPG capacity (kW)} \times G_r}{\text{life time (year)} \times 8760 \times LF}, \quad (24)$$

$$b = (\text{RPG Fuel cost (\$/kWh)} + \text{RPG O \& M cost (\$/kWh)}), \quad (25)$$

where G_r is the annual rates of benefit and LF is the load factor of RPGs.

The investment cost (C_{RPC}) of the reactive power compensator can be calculated using Equation (26). The different components of C_{RPC} are installation cost (e_i), purchase cost (C_{ci}), and the actual lifetime of the RPC.

$$C_{RPC} = \frac{\sum_{i=1}^{N_{RPC}} (e_i + C_{ci} |Q_{ci}|)}{\text{lifetime (year)} \times 8760} \quad (26)$$

where N_{RPC} is the total number of RPC units and Q_{ci} is the reactive power capacity of i^{th} RPC unit. The generated cost of the generating stations (C_{Grid}) can be estimated as follows:

$$C_{Grid} = P_{gGrid} \times P_{rGrid}, \quad (27)$$

where P_{gGrid} is the real power produced by the generating station and P_{rGrid} is the generated power cost at generating station. The economic characteristics of RPGs are dependent on their type. To increase the RPGs penetration level, two types of RPGs are considered (PV and WT) as shown in Table 9. Moreover, generated power costs at generating stations are considered to be 0.044 $\$/kWh$ and e_i and C_{ci} are considered equal to 1000 and 30 $\$/kVAR$, respectively [6].

Table 9. RPG specifications.

Cost Components	PV	WT
Capital cost ($\$/kW$)	3985	1822
Rated capacity (MW)	1	5
Life time (year)	20	20
O&M costs ($\$/kWh$)	0.01207	0.00952
Fuel cost ($\$/kWh$)	-	-

The total cost of RPG units, RPCs, and grid were calculated based on the mathematical equations described above and the results are shown below:

- Generating cost of the uncompensated system was \$52,478/hr.
- Generating cost of the compensated system for case 5, i.e., best case (optimal placement and sizing of RPC and RPGs at 0.85 LPF) was \$33,449/hr.
- From the results, it was found that the total cost savings of 36.26% were obtained when RPGs at 0.85 LPF and RPC were allocated optimally in the IUPS.

7.3. Comparison with Existing Work

A comparative study was made for case 2 with the Algerian transmission system of 114 buses. The differential evolution (DE) method is adopted to optimally locate and size the 3 PV-based DGs (similar to RPGs at UPF) and the results are shown in Table 10.

Table 10. Comparative study between the proposed system and Algerian transmission system.

Techniques	PV DGs Size in MW (Bus No.)			Total RPG Size (MW)	Power Loss (MW)	Loss Reduction (%)	Minimum Voltage (p.u.)	VDI (p.u.)	VSI (p.u.)
Uncompensated	-			-	33.45	0	0.9571	-	-
DE [36]	144.61 (6)	149.11 (44)	49.26 (66)	342.98	27.59	17.52	0.97261	-	-

From the results, it can be observed that the proposed LSF Based PSO algorithm minimized the power loss up to 49.74% whereas the DE reduced the power loss only up to 17.52%. Conventionally, many of the research works are carried out on optimal allocation of distributed generations (DG) and/or capacitor banks (CBs) in the power system. However, these results of optimization may not meet the RE potential in real-time assessment. This study primarily aimed to optimally allocate the RPGs and RPCs using the proposed methodology. Secondly, the candidature locations obtained from the optimization technique are compared with the available resources by demonstrating potential assessments. In the future, the resource assessment is integrated as a vital constraint in the existing objective functions to reallocate the RPGs.

8. Assessment of RE Potential in the Selected Location

The local and worldwide community is trying to progressively move to RE sources by reducing their economic dependence on them. Attesting this, the current assessment work was intended to be carried out for the Chennai transmission system of Tamil Nadu State of India as a study area. The study area includes two urban and one suburban area of Chennai, Tamil Nadu as shown in Table 11. These selected areas were chosen from case 5 of test scenarios. The latitude and longitude of the study area are presented in Table 11.

Table 11. Latitude and longitude of the study area.

Sl. No.	Bus No.	Name of the Area	Latitude and Longitude
1	4	Mylapore	13°1'54" N, 80°16'12" E
2	9	Gummidipoondi	13°25'50" N, 80°4'55" E
3	11	Tharamani	12°59'6" N, 80°14'26" E

8.1. Framework and Methodology

The MERRA-2 data of NASA covering the entire world are taken as underlying data. These data consist of wind speed, solar irradiation, and ambient temperature that are needed for wind-solar energy assessment, and have $0.5^\circ \times 0.5^\circ$ spatial resolution [57]. The annual wind speed and solar irradiance of selected locations of the IUPS are shown in Figures 13 and 14 respectively. Notably, the annual wind speed takes the upper hand in June for all locations and a maximum of 5.5 m/s is recorded in the Tharamani location. Although Gummidipoondi and Mylapore locations show reduced wind speed compared with the other location Tharamani, it has the potential to evacuate a higher rate of wide power output due to its better average wind speed throughout the year.

Figure 13. Annual wind speed of selected locations (m/s).

Figure 14. Annual solar irradiance at selected locations (kwh/m²).

The annual solar irradiance of the selected locations was not showing greater differences but the irradiance rate displays greater in month of March. Similar to wind characteristics, the average rate of solar irradiance had the potential to generate huge power evacuation.

8.2. RE Potential Based on the Land Use Factor

It is a known fact that the total area of the selected locations cannot be utilized for power evacuation practically. Therefore, the direct land acquisition factor for solar PV and wind farms are considered for urban area and semi-urban locations. Further, the minimum estimates of the land-use factor of 2.25–9 MW/km² for wind and 7.5–30 MW/km² for solar PV are considered [27]. The maximum and minimum rates of solar-PV and wind energy output power that can be generated at the selected locations are given in Table 12.

Table 12. Area-wise technical potential for wind and solar PV energy generation.

Sl. No.	Bus No.	Name of the Area	Area (km ²)	Land Use Factors			
				Wind Potential (MW)		Solar PV Potential (MW)	
				9 MW/km ²	2.25 MW/km ²	30 MW/km ²	7.5 MW/km ²
1	4	Mylapore	3.914	35.23	8.81	117.42	29.36
2	9	Gummidipoondi	10	90	22.5	300	75
3	11	Tharamani	3.31	29.8	7.45	99.3	24.83

The monthly power output curve of the selected locations was computed using the PVGIS software package [58] and displayed in Figure 15. The software-based on the data inputs evaluates solar electricity production. It is assumed that the solar PV systems are south-facing fixed tilt with their tilt equal to the latitude of the location [27]. It is observed that a higher rate of power evacuation was recorded from the Gummidipoondi location compared with other locations. On other hand, Tharamani locations show a lesser magnitude.

Figure 15. Monthly solar PV output at selected locations.

Similarly, monthly wind power output curves were determined and demonstrated in Figure 16. It is observed that two peaks were recorded in May and August and one valley is noted in October. Notably, that the monthly variations had the tendencies for higher rate power evacuation from selected sites but with different magnitudes.

Figure 16. Monthly wind energy output at selected locations.

The monthly variations of hybrid RE resources, i.e., both solar and wind are presented in Figure 17. Solar energy complements wind energy during the daytime and wind energy was dominating throughout the year. As the minimum and maximum land acquisition factor for solar PV was high (7.5–30 MW/km²) compared to the wind (2.25–9 MW/km²), the solar energy output was dominating the wind energy output in all the selected locations.

Figure 17. Monthly average solar and wind energy outputs at selected locations.

Considering all the above, the comparative analysis between the outcome of the potential assessment and RPGs sizing rating is demonstrated in Figure 18. It is noted that the potential of the selected locations was greater compared with RPGs rating particularly for Gummidipoondi and Tharamani locations. On the other hand, the potential of the Mylapore location was not great when compared with RPG ratings though it recorded higher annual wind speed and irradiation. However, increasing or utilizing the land-use factor to a greater extent through the solar rooftop in the Mylapore location may increase the RE potential noticeably. The overall comparison demonstrates that the potential assessment of the selected locations was more suitable for hybrid renewable power generation to improve the stability of the overall power system.

Figure 18. Comparative analysis between potential assessments versus RPGs sizing.

9. Conclusions

This work established renewable energy potential assessment with optimal allocation of RPGs and RPCs for the Indian utility transmission systems using a PSO algorithm. Its effectiveness was validated with five different configurations with multiobjective functions such as minimum power losses, minimum voltage deviation, and maximizing voltage stability. Wherein, the integrated setup of RPCs and RPGs operating at leading power factor displays superior performance. The overall power loss of the transmission system was reduced to 52.27%. Moreover, the voltage profiles of all nodes were accomplished within the band limit. Additionally, the index of voltage stability and voltage deviation was recorded to their finest scale. Subsequently, the potentials of solar and wind energy resources were assessed for candidature locations obtained using the PSO algorithm. The

RE technical potential at these selected locations was calculated. Based on the obtained results, a more reliable operation of the IUPS can be possible by integrating RE resources at candidature locations.

The RPG penetration in transmission grids helped to balance the power demand between different regions/areas. Additionally, it could effectively overcome the monsoon phenomenon by utilizing the resources available in other regions/areas cost-effectively. Further, it might enhance long-term planning and transmission investment plans that can offer optimal technoeconomic operation for the utility. The extension of this work focuses on the relocation of RPGs based on the available resources at candidature locations based on uncertainty and inadequacy factors. Additionally, an advanced optimization technique with various integration controls can be investigated for effective RPG penetration by considering vital constraints such as technical, economic, and environmental.

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Appendix A

Table A1. Generator and load bus data of the IUPS.

Bus No.	Generation		Load	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	-	-	-	-
2	225	-	-	-
3	-	-	142.5	7.5
4	-	-	250	26
5	-	-	137.5	10
6	-	-	22.5	7
7	-	-	11	7.5
8	-	-	4	1
9	-	-	167.5	12
10	-	-	7.5	3.5
11	-	-	130	10
12	-	-	35	10
13	-	-	25	2
14	220	-	-	-
15	-	-	38.5	6.5
16	-	-	120	20
17	-	-	8.5	4
18	110	-	-	-
19	220	-	-	-

Table A2. Transmission line data of the IUPS.

Line No.	From Bus	To Bus	Impedance (p.u.)		MVA Rating
			R	X	
1	1	9	0.01188	0.061	175
2	1	10	0.00212	0.0068	125
3	1	5	0.00212	0.011	150
4	1	3	0.00274	0.0124	250
5	1	7	0.0288	0.1486	50
6	1	2	0.00548	0.0282	100
7	2	3	0.00304	0.0156	225
8	2	7	0.0316	0.1626	50
9	2	5	0.0067	0.0344	62.5
10	14	15	0.0412	0.2082	275
11	18	17	0.0558	0.2864	250
12	19	13	0.039	0.2	262.5
13	9	8	0.01188	0.061	25
14	9	10	0.025	0.1284	62.5
15	5	6	0.00244	0.0124	50
16	6	10	0.00974	0.05	25
17	5	10	0.0118	0.061	25
18	3	4	0.00274	0.0124	300
19	7	10	0.01492	0.0766	100
20	17	7	0.01674	0.086	187.5
21	10	11	0.01522	0.0782	175
22	10	12	0.0073	0.0376	50
23	10	16	0.00822	0.0422	65
24	13	10	0.03138	0.1612	200
25	17	16	0.02772	0.1424	162.5
26	17	13	0.0137	0.0704	150
27	17	15	0.0426	0.219	112.5
28	13	15	0.0296	0.1518	100

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