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# Power Factor Optimization of Distributed Generations in Distribution Networks Based on Improved Particle Swarm Optimization Method

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**Abstract.** The gradually extensive penetration of small-scale distributed renewable generators in existing medium-voltage power distribution networks highlights many technical challenges which call for urgent solutions from power utilities. This paper attempts to optimize the power factor of distributed generators (DGs) integrated in distribution networks and presents a novel algorithmic solution. With the aim of minimizing power loss whilst maintaining the node voltage, the problem is formulated with a mathematical model elaborating the DGs and a set of constraints in distribution networks and addressed through adopting an extended particle swarm optimization (PSO) approach. The suggested algorithm is assessed through numerical simulation experiments with the IEEE 33-bus system and the outcome shows that the optimization algorithm can effectively reduce the power loss and promote the node voltages across the overall distribution network.

## Introduction

In most recent years, a large number of small-scale distributed generators (e.g. wind turbines, Combined Heat and Power (CHP) and solar energy) are gradually connected and embedded in current power distribution networks. This is universally acknowledged as the most significant reshape of current power utility due to the reasons of high price of fossil fuels and the pursuit of future low-carbon economy. With the massive penetration of DGs, the power distribution network becomes an active system interconnecting distributed generators and various loads with bidirectional power flows. It should be noted that many available renewable energy resources are with the intermittent nature to make them difficult to predict and control. Obviously, this makes the control and management of power distribution network with DGs a challenging task, e.g. voltage raise effect, increased fault level, protection degradation, and altered transient stability [1].

It can be envisaged that a massive number of DGs will be integrated into power distribution grids across a large geographical span in the near future. This makes the impacts of DGs distributed across the distribution network more significant as the DGs are often close to the power loads and operate in a complex and dynamic fashion. Under such circumstances, the power distribution networks with DGs require more advanced management and control. Our previous work has highlighted the key challenges of managing medium-voltage distribution networks with DGs and investigated a distributed control paradigm to address the issue, with a particular focus on the communication requirements and reinforcements [2]. Apart from the emerging technical challenges due to DG integration, the appropriate allocation and power injection of distribution generation could greatly reduce the power loss during power delivery as well as improve the quality of power supply. This paper follows this line of research and exploits the optimization of DG power injection so as to improve the utilization efficiency of the DGs, and hence improve the operation of the overall active power distribution grids. Much research efforts have been made in respect to the approaches to maximize the benefits of DG integration through proper control of connected DGs. In [3], the authors presented an optimization approach based on the Genetic Algorithm (GA) under the condition that the number, location and capacity of integrated DGs are uncertain. In [4], a GA based approach is proposed to determine the most appropriate locations and power injections of DGs in the planning or reinforcement stage of the energy networks. Also, a centralized reactive control solution with grid-connected inverter is exploited in distribution networks with DGs and the optimization of reactive power is addressed using GA [5]. The impacts of DGs on the node voltages are studied and a set of suggestions of DG location are presented in [6]. In [7], a hybrid optimization algorithm for DG injection power and distribution network reconfiguration based on particle swarm optimization (PSO) is proposed.

In fact, the location of DGs to be connected to the power distribution networks cannot be optimal as they are often geographically dispersed with various capacities. In addition, the active and reactive power of DGs can be effectively decoupled and controlled separately through the adoption of inverters in DGs [5]. Thus, this paper attempts to optimize the power factor of connected DGs within their allowable capacities to minimize the power loss in distribution networks, given that the DG locations and capacities are pre-determined. To the best knowledge of authors, there is little research work available in the literature to address the DG power factor optimization issue in the power system at the distribution level.

The key contribution made in this paper is that we carry out the pioneer study on the DG power factor optimization issue by adopting an improved PSO approach in the context of power distribution networks with integrated DGs and confirm its effectiveness in achieving optimal DG power factor and node voltage promotion as well as power loss reduction through numerical simulations. The reminder of the paper is organized as follows: we firstly present the problem formulation and the mathematical model; then we overview the improve PSO method which is adopted in this work, followed by the simulation assessment and a set of numerical results using the IEEE 33-bus system; finally, some conclusive remarks and future work are presented.

## Problem Formulation and Mathematical Model

In this paper, we attempt to address the power factor optimization of distributed generators in distribution networks by using power loss as the optimization metric so as to improve the quality of power supply. With such consideration, we formulate the DG power factor optimization problem with the aim of minimizing power loss in the overall distribution network subject to a set of constraints.

### A. Objective function

Based on the above discussion, the DG power factor optimization problem can be formulated as an optimization problem with the objective function defined as follows:

$$Min\, f(x) = Min L = Min \sum_{i=1}^{N_1} R_i \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{1}$$

where $L$ is the power loss of the whole distribution network and $N_1$ is the number of energized branches in the distribution network. Also, $R_i$ is the resistance of $i^{th}$ branch, $P_i$ and $Q_i$ are the active power and the reactive power flowing though $i^{th}$ branch respectively, and $V_i$ is the voltage at the end of $i^{th}$ branch. To obtain the values of $L$ in specific distribution networks, we adopt the back/forward sweep method for the power flow calculation, which is particularly suitable for distributed networks.

### B. Constraints

In the problem formulation, a set of constraints need to be met during the power factor optimization in power distribution networks with DGs. In this work, we consider three different constraints, namely power flow constraint, node voltage constrain and branch power constraint.

1) Power flow constraints with DG:

$$P_i + P_{DG_i} = P_{D_i} + V_i \sum_{j=1}^{N_b} V_j \left( G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right) \tag{2}$$

$$Q_i + Q_{DG_i} = Q_{D_i} + V_i \sum_{j=1}^{N_b} V_j \left(G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}\right) \tag{3}$$

where $N_b$ is the number of nodes, $P_i$ and $Q_i$ are the active and reactive power injection respectively at the $i^{th}$ node, $P_{DG_i}$ and $Q_{DG_i}$ are the active and reactive power injection respectively from DG at the $i^{th}$ node, $P_{D_i}$ and $Q_{D_i}$ are the load active and reactive power at the $i^{th}$ node respectively, $V_i$ is the voltage of $i^{th}$ node, while $V_j$ is the voltage of $j^{th}$ node, $G_{ij}$ and $B_{ij}$ are conductance and susceptance of the line from $i^{th}$ to $j^{th}$ node, $\delta_{ij}$ is the phase angle difference of the $i^{th}$ and $j^{th}$ node.

2) The node voltage needs to meet the following constraints:

$$V_{i\,min} < V_i < V_{i\,max} \tag{4}$$

where $V_{i\,min}$ and $V_{i\,max}$ are the minimum and maximum acceptable voltages of the $i^{th}$ node, respectively.

3) Branch power constraints:

$$S_{ij}^{line} \leq S_{ij\,max}^{line} \tag{5}$$

where $S_{ij}^{line}$ is the apparent power flowing form $i^{th}$ node to $j^{th}$ node and $S_{ij\,max}^{line}$ is the maximum acceptable value of $S_{ij}^{line}$.

## Algorithm Design and Implementation

A. Particle Swarm Optimization

The Particle Swarm Optimization (PSO) algorithm was firstly proposed by doctor Eberhart and Kennedy in 1995, as a primary intelligent optimization approach by simulating social iterations. The standard PSO (SPSO) algorithm works as follows: it is initialized with a population of random solutions (i.e. particles) and each particle is associated with two states (current position and current velocity). The solution is sought through a set of particles (i.e. the potential solutions), while the search trajectory is adjusted in accordance with the inspiration from the flying of a flock of birds. A particle, as the time passes through its quest, adjusts its position according to its own “experience” as well as the “experience” of neighboring particles.

In an assumed d-dimension target search space, let the position and velocity of the $i^{th}$ individual be denoted as $X_i(x_{i1}, x_{i2}, x_{i3} \dots \dots x_{id})$ and $V_i(v_{i1}, v_{i2}, v_{i3} \dots \dots v_{id})$. The best previous experience of the $i^{th}$ particle is recorded and denoted as $p_{besti}(p_{besti1}, p_{besti2}, p_{besti3} \dots \dots p_{bestid})$. The best value among all individuals’ experiences in the group is also stored and denoted as $g_{besti}(g_{besti1}, g_{besti2}, g_{besti3} \dots \dots g_{bestid})$. For each iteration, the velocity and position of individual particles are updated based on the following formulas:

$$v_{id}^{k+1} = \omega v_{id}^{k} + c_1 r_1 \left(p_{bestid}^{k} - x_{id}^{k}\right) + c_2 r_2 \left(g_{bestid}^{k} - x_{id}^{k}\right) \tag{6}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{7}$$

where $\omega$ is the inertia coefficient which in general takes the value of 0.4~0.9, and $c_1$ and $c_2$ are acceleration constants which pull each particle toward $p_{besti}$ and $g_{besti}$ positions, their general value is 2.0, $r_1$ and $r_2$ are all random number on [0, 1].

### B. Improved Particle Swarm Optimization

In this work, we adopt an Improve Particle Swarm Optimization (IPSO)[8] based on the modified inertia weight. Then analysis results about the astringency of PSO show that inertia coefficient $\omega$ have a great influence on the optimal performance of PSO. The higher value $\omega$ will result in better PSO global search capability but worse local searching ability. Thus, we flexible adjust the value of $\omega$ to carry out the Improved Particle Swarm Optimization. During each iteration, we observe the difference between particles in their evolutions, and give adaptive inertia weight to individual particles in accordance to their own positions, which enables each particle gradually draw close to the directional preponderance, and the best trade-off between global search capability and local searching ability can be obtained. As a result, the optimization algorithm could achieve fast astringency and enhanced search capability. The evolution of particles can be adapted can be implemented through the formula (8)-(11) as follows:

$$z_{id} = [c_1 r_1 (p_{bestid}^k - x_{id}^k) + c_2 r_2 (g_{bestid}^k - x_{id}^k)]/v_{id}^k \tag{8}$$

$$\omega_{id}^k = \{\omega_{max} - [(\omega_{max} - \omega_{min})k/inter_{max}]\}[1/(1 + exp\ (\frac{-k}{inter_{max} z_{id}})] \tag{9}$$

$$v_{id}^{k+1} = \omega_{id}^k v_{id}^k + c_1 r_1 (p_{bestid}^k - x_{id}^k) + c_2 r_2 (g_{bestid}^k - x_{id}^k) \tag{10}$$

$$x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \tag{11}$$

where $z_{id}$ is an adaptable parameter which changes its value based on the current iteration number. $\omega_{max}$ and $\omega_{min}$ are the minimum acceptable and the maximum acceptable inertia weight respectively, $k$ is the current iteration number, and $inter_{max}$ is the pre-defined maximum number of iterations during the optimization.

## Simulation Experiments and Numerical Results

In this paper, we take the IEEE 33-bus system [9] with three DGs as an example power distribution network in the numerical simulation experiments, as illustrated in Fig. 1. The IPSO algorithm is implemented with the MATLAB environment and assessed with the PC (Win 7 operating system, 2GB memory and 3G Hz CPU) in MATLAB version 2010a.

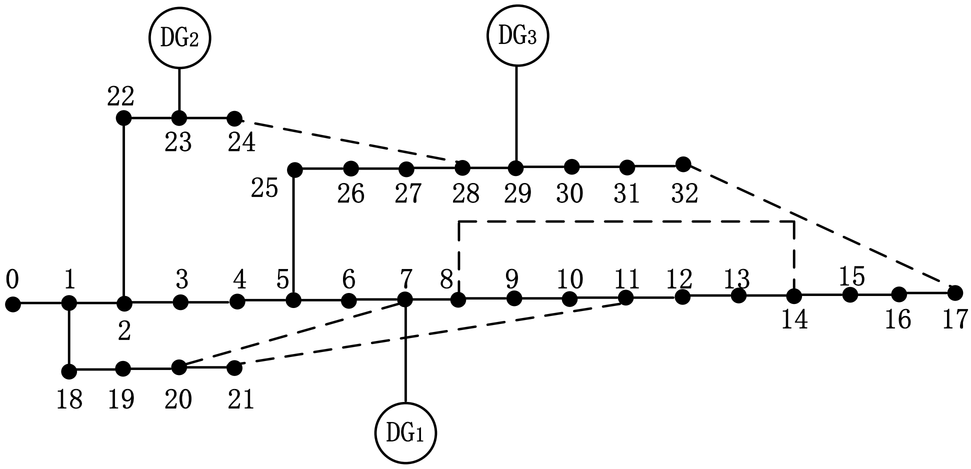

Fig. 1: The IEEE 33-bus system with 3 DGs

In the simulated case distribution network, the rated voltage is set as 12.66 kV, and the total power load is 3715kW+j2300kvar. In respect to the DG locations, previous studies have pointed out that the DGs are more appropriately to be located in the middle or later section of long branches in the distribution network, or near the nodes connecting with heavy power loads [6], so as to reduce power loss due to power flow transmission. It is assumed that there are 3 DGs connected with the case network at 7th, 23th and 29th node respectively. For the sake of simplicity, we also assume that all DGs have the same capacity of 1000kW, but their power factors can be different due to the fact that the active and reactive power can be decoupled and control respectively. Prior to the power factor optimization, we consider the power factors of all DGs as 1. The number of particles in the IPSO algorithm is set to 20 with the optimization parameters of $\omega_{max} = 0.9$, $\omega_{min} = 0.4$, $c_1 = c_2 = 2$ and the maximum number of iterations is set to100. The performance evaluation result of power factors optimization is showed in Table 1.

Table 1: The DG power factor, overall power loss (before vs. after optimization)

| | Power factor | | | Overall power loss[kW] |
|---|---|---|---|---|
| The node ID with DG | 7th | 23th | 29th | |
| Before optimization | 1 | 1 | 1 | 116.7 |
| After optimization | 0.881 | 0.898 | 0.682 | 25.4 |

The result of power loss also shows the performance improvement through optimization indicating power loss reduction of about 80%, as shown in Table 1.

In addition, the node voltage may get benefit from our optimization. The simulation result of node voltages by the use of IPSO algorithm is shown in Fig. 2 in comparison with the scenario without optimization. It can be seen that prior to the power factor optimization, the minimal node voltage across the power distribution network is 0.9534 pu. Through the optimization, the node voltage has been promoted to be 0.9633 pu. Significant improvement of node voltage can be observed from the simulation result for network node 0 to node 26, although some network nodes experience voltage sags, e.g. 27*th* node to 32*th* node. This is mainly due to the power loss optimization is carried out at the scale of overall distribution network rather than in respect to individual nodes, and hence the average node voltage can be improved.

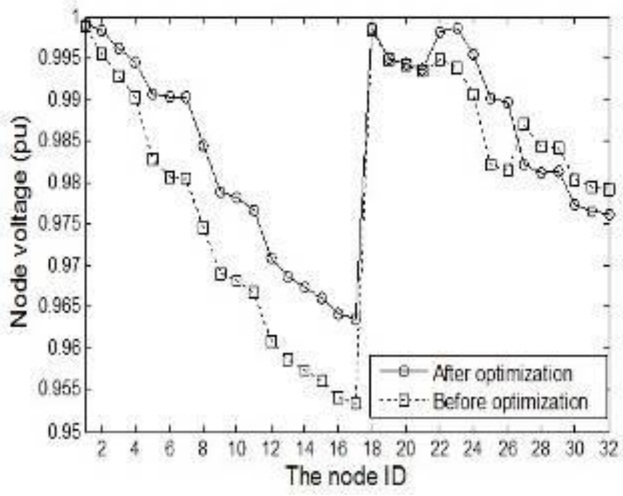

Fig 2: The network node voltages (with vs. without optimization)

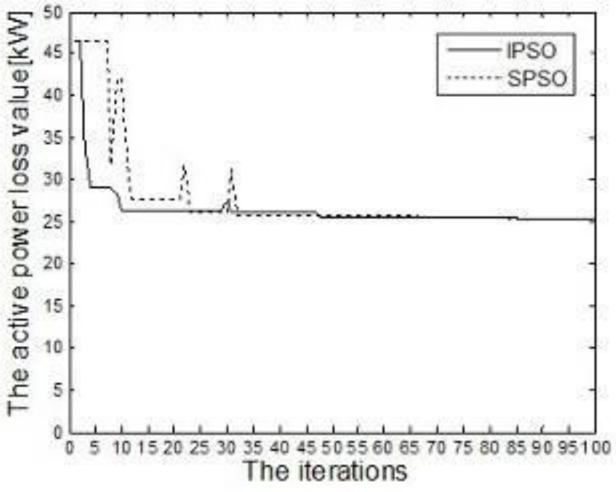

Fig 3: Power loss vs. the number of iterations (SPSO vs. IPSO)

We also examine the power loss performance in the simulated case distribution network with the increasing number of iterations in IPSO in comparison the standard PSO. In Fig. 3, the result demonstrates that the IPSO could converge after about 10 iterations during the optimization of power loss, while in SPSO, not until 30 iterations that the fitness can be convergence. We can also see that the convergence is much steadier in IPSO than in SPSO.

## Conclusions and Future Work

In this paper, we exploited the application of an improved PSO approach to the power factor optimization of DGs through minimizing the power loss of the overall distribution network. The problem is formulated with the mathematical model and the suggested algorithm has been assessed through the numerical simulation experiments with IEEE 33-bus system by using the standard PSO algorithm as the comparison benchmark. The result demonstrates that the ISPO algorithm could significantly minimize the power loss and promote the network node voltages across the overall distribution networks with DGs as well as improved converge time. In respect to the future work, we will further investigate the power factor optimization by incorporating different distribution network scales and topologies, and DG diversity in terms of DG power generation and the interactions among different integrated DGs.

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