Particle Swarm Optimization Based Reactive Power Dispatch for Power Networks with Distributed Generation

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PARTICLE SWARM OPTIMIZATION BASED REACTIVE POWER DISPATCH
FOR POWER NETWORKS WITH DISTRIBUTED GENERATION

A Thesis
Presented to
The Faculty of Daniel Felix Ritchie School of Engineering and Computer Science
University of Denver

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Xiao Kou
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Advisor: Dr. David Wenzhong Gao
Abstract

Reactive power is critical to the operation of the power networks on both safety aspects and economic aspects. Unreasonable distribution of the reactive power would severely affect the power quality of the power networks and increases the transmission loss. Currently, the most economical and practical approach to minimizing the real power loss remains using reactive power dispatch method.

Reactive power dispatch problem is nonlinear and has both equality constraints and inequality constraints. In this thesis, PSO algorithm and MATPOWER 5.1 toolbox are applied to solve the reactive power dispatch problem. PSO is a global optimization technique that is equipped with excellent searching capability. The biggest advantage of PSO is that the efficiency of PSO is less sensitive to the complexity of the objective function. MATPOWER 5.1 is an open source MATLAB toolbox focusing on solving the power flow problems. The benefit of MATPOWER is that its code can be easily used and modified.

The proposed method in this thesis minimizes the real power loss in a practical power system and determines the optimal placement of a new installed DG. IEEE 14 bus system is used to evaluate the performance. Test results show the effectiveness of the proposed method.
Acknowledgements

I would like to express my sincere gratitude to my advisor Prof. David Wenzhong Gao, for his selfless support during my two years study at the University of Denver. Dr. Gao’s rigorous attitude towards scholarship and humility deeply impressed me and will benefit me for life.

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Chapter One: Introduction

1.1 Background and Motivation

Reactive power is critical to the operation of the power networks on both safety aspects and economic aspects. Rational reactive power dispatch scheme can improve the power quality as well as reduce the real power loss. On the contrary, if the reactive power is unreasonably allocated, then it will bring great economic losses and might even threaten the security of the power grid.

It has been proved that the New York Blackout in 1977 and the Tokyo Blackout in 1987 were both caused by the deficiency of reactive power during the peak load hours [1]. These blackouts brought social disruptions and hundreds of millions of dollars in loss. On August 14, 2003, the Northeast Blackout affected about 55 million people in the mid-western part of the United States and Ontario province in Canada. One of the main reasons that causing this blackout is also due to the reactive power shortage [2-3].

Reactive power also plays a prominent role in minimizing the real power loss of the power networks. Reactive power dispatch approach can significantly reduce the power factor angle of each bus, thus cutting the overall energy losses. Each year, a large amount of electricity is wasted on the transmission or distribution lines around the world. According to the estimations from the U.S. Energy Information Administration, the annual transmission and distribution losses in the United States can reach as much as 6% [4]. Moreover, most of this loss occurs at the distribution level. This real power loss not
only causes energy waste and produces extra carbon emission, but also increases the 
generation cost.

Along with the development of the economic, the scale of the power grid also 
keeps growing. In some areas, however, the construction and upgrading of the power grid 
did not keep pace with the growth of the loads. Then a severe shortage of the reactive 
power would appear. For the purpose of minimizing the real power loss, utility 
companies can either change the structure of the power grid or replace the old wiring 
with lower impedance lines. However, both of these methods requires investing large 
amounts of money. The simplest and most economical way remains reactive power 
dispatch method. In the early days, the starting point of reactive power dispatch is to 
improve the power factor at each end user by installing reactive power compensators. 
This approach, of course, can reduce the total power loss. But in order to get the 
maximum profit, electricity grid designers have to take a more holistic view and calculate 
the power flow.

1.2 Reactive Power Compensation Techniques

There are many reactive compensation techniques. Fig. 1.1 shows a simple five 
bus system without using any reactive power compensators. This model is developed in 
PowerWorld Simulator 17 [5]. The real and reactive power output of the generators are 
304 MW and 129 MVar, respectively. Since there is no capacitor in this system, the 
generator will take the whole burden of both real power loads and reactive power loads.
Running the simulation, a 4.27 MW real power loss and 8.55 MVar reactive power loss can be achieved.

![Five Bus System without Power Factor Correction](image)

**Figure 1.1 Five Bus System without Power Factor Correction**

In order to reduce the power loss, reactive power dispatch techniques can be employed. The easiest way to compensate the reactive power is to connect the capacitors in parallel with the loads. This approach can be further divided into single power factor correction, group power factor correction, and bulk power factor correction [6].

1.3.1 Single Power Factor Correction

In single power factor correction model, each load has a shunt capacitor. The capacitor and the load it serves share the same switch, so no extra control devices are needed in this scheme. When the capacitors inject reactive power, both transmission loss and voltage drop will decrease. In this case, the real power loss is 3.84 MW and the reactive power loss is 7.67 MVar. The disadvantage of this method is that the shunt
capacitors are not fully utilized all the time. Since the load and its shunt capacitor use the same switch, the capacitor will not compensate reactive power if the load is turned off.

Figure 1.2 Single Power Factor Correction

1.3.2 Group Power Factor Correction

To overcome the defect of single power factor correction method, a more effective way called group power factor correction was proposed. The PowerWorld model for group power factor correction method is shown in Fig. 1.3.

In this method, instead of just compensating only one load, one capacitor could handle a group of loads. Also, the reactive power injection are controlled by a microprocessor based on the real-time reactive power demand. In the PowerWorld model, the active power loss is 3.96 MW and the reactive power loss is 7.91 MVar, which are slightly higher than those in single power factor correction method. However, the efficiency of the shunt capacitors is greatly improved.
1.3.3 Bulk Power Factor Correction

The third power factor correction method is called bulk power factor correction, as depicted in Fig. 1.4. The shunt capacitor bank is in charge of the whole system, and it is directly connected to the PV bus.
Since most of the loads in the electric power systems are inductive loads, they will consume large amounts of reactive power. The reactive power has to be obtained from somewhere in the network. If all the reactive power is produced from one place, then the real power loss will be enormous. This conclusion is demonstrated in Fig. 1.4, both real power loss and reactive power loss is much greater than the previous two schemes. Therefore, the principle of reactive power dispatch is compensating reactive power at where the loads consume.

1.3 Literature Review

In this thesis, the approach of reactive power dispatch is to adjust the values of control variables and find the optimal placement of new installed DG. Since both objective function and equality constraints are nonlinear, the main emphasis is on managing the nonlinear function problem with mixed discrete control variables.

The first reactive power dispatch method was suggested by N. M. Neagle and D. R. Samson in 1956. In [7], Neagle and Samson analyzed two types of load models. In the first model, the loads are equally distributed along the feeders. However, this type of system is an idealized model, and it does not exist in real life. So in their second model, they assume the magnitudes of the loads in a feeder are proportional to their distances from the substation. The shortcoming of this method is that there is only one generator in their models. Thus, this method is not suitable for those power grids with distributed generation.
After that, interior-point method (or barrier method) is introduced to solve the reactive power dispatch problems. The interior-point method belongs to linear programming. The principle of linear programming is to expand the nonlinear functions and constraints into Taylor’s series expansions. Only the first-order terms and the constant terms need to be considered. The advantage of this method is linear programming theory is mature and the computation time is short. Nonetheless, since the objective function of reactive power dispatch problem is not convex, many local optima exist. Therefore, the linear programming method is very likely to get trapped into one of these local optima and cannot achieve a global optimal solution. Moreover, linear programming ignores the higher-order terms, so the accuracy of the results can also be affected.

The quadratic programming method is another method that can be used to solve the reactive power dispatch problem [8]. Quadratic programming is more adaptable to the nonlinear characteristic of reactive power dispatch problem than linear programming. Furthermore, its nice convergence characteristic is also helpful. The disadvantage is that quadratic programming does not work very well for the high dimensional problems. As the dimension increase, the computation time would increase dramatically.

Since the 1990s, heuristic methods like Simulated Annealing (SA) and Genetic Algorithm (GA) are getting more and more capable and grab plenty of attentions [9].

Simulated annealing imitates the heating and cooling process of the metal, and it was suggested by Metropolis in 1953. SA use random search and iteration methods to obtain the optimal solution. In metallurgy, the goal of annealing is to get the best metallic
crystal. When the cooling process is finished, the energy of the material becomes lowest. This process is similar to optimizing the reactive power. The goal of reactive power dispatch in this thesis is to get the minimum real power loss. The power loss will be reduced as the iterations proceed. The disadvantage of SA is that the parameters of simulated annealing need to be carefully chosen. Inappropriate parameters selection would greatly increase the computation time. T. Sousa et al. put forward a modified simulated annealing method to search for the optimal size and placement of compensators in IEEE 14 buses system [10]. In [11], M. Gitizadeh proposes another fuzzy-based reactive power dispatch method by using simulated annealing.

The genetic algorithm is based on mimicking the evolutionary process, and it was presented by J. Howard in 1975. Genetic algorithm is totally different from the traditional optimization methods. The feasible solutions in GA are compared to chromosomes. Selection, crossover and mutation operation are repeatedly conducted to propagate better individuals in the next generation. GA provides a framework for solving the nonlinear multi-objective complex problems, and it has already been used in many areas, such as control, signal processing, robotics, and economics. The advantages of GA are its practicability, high-efficiency, and robustness. A genetic algorithm toolbox GAOT (Genetic Algorithm Optimization Toolbox) was developed by North Carolina State University and posted for free online. The disadvantage of GA is its prematurity and diversity problems. In [12], GA was proposed to solve the reactive power devices placement in IEEE 14 buses system. Another reactive power optimization by using GA is performed in IEEE 34 buses system in [13].
The artificial neural network is an algorithm based on the neural networks of animals [14]. The biggest advantage of artificial neural networks is its self-teaching ability. For instance, given a certain amount of data, artificial neural networks algorithm can gradually identify similar data through self-teaching. This benefit has important significance on forecasting. Paper [15] presents a combined artificial neural networks and fuzzy sets to solve the optimal reactive power control problems. In [16], the artificial neural network algorithm is used on the online optimal shunt capacitors dispatch to reduce the input variables and to get better computation speed.

To sum up, each algorithm has its advantages and disadvantages. Therefore, local conditions need to be considered in choosing the appropriate algorithm for solving the reactive power dispatch problems in different power networks.

1.4 Expected Contribution

This thesis summarizes the status of reactive power dispatch and compares different global optimization methods. A modified MATPOWER code utilizing particle swarm optimization algorithm is developed to solve the reactive power dispatch problem in the power systems.

The expected contribution of this thesis mainly includes the following aspects:

1. Applying particle swarm optimization algorithm to adjust the values of control variables (voltage magnitudes, tap positions, and shunt capacitance) in the power networks to minimize the real power loss.
2. Identifying the optimal placement of a new installed distributed generator in an existing power system.

3. Introducing MATPOWER 5.1 toolbox to calculate the power flow and manage the equality constraints in the reactive power dispatch problems.
Chapter Two: Global Optimization Methods

In most cases, the objective functions in nonlinear optimization problems are not convex. Traditional optimization methods (such as gradient-based approaches) can only find local optimal values. Moreover, the results from traditional optimization methods often have strong connections with the initial guess. To overcome these problems, global optimization methods are suggested in this thesis.

Global optimization methods can only guarantee to achieve acceptable solutions. Usually, finding the global optimal results will take plenty of time and resources. Sometimes it is not profitable to do so. If the improvement is insignificant, then it is probably a bad deal to take the time to find the global optimal solution. Therefore, if the result is very close to the global optimal solution, it can be viewed as an acceptable solution.

In global optimization methods, some concessions have to be made (for instance, increasing their objective function values in some iterations) to allow potential solutions to escape from the local optimum. Most of the time, there is no way to determine if a global optimal value is already achieved or not, so global optimization methods usually need to take plenty of iterations without bias. This requirement will in turn force the scheme of the global optimization methods to be as simple as possible.

In the following sections of this chapter, three of the most representative heuristic global optimization methods (simulated annealing, genetic algorithm, and particle swarm
optimization) are introduced. These three global optimization methods can be easily
programmed and are well suited for solving reactive power dispatch problems.

2.1 Simulated Annealing

Simulated annealing (SA) was proposed by Kirkpatrick in 1983. In order to
change the physical properties of the metal materials and increase the ductility, the metal
is first heated to its melting temperature and then cooled down [17]. The optimization
process of simulated annealing resembles the process of annealing in metallurgy. Table
2.1 lists some technical terms of simulated annealing and their corresponding annealing
words in metallurgy [18].

<table>
<thead>
<tr>
<th>Simulated Annealing Terms</th>
<th>Annealing Terms in Metallurgy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasible solutions</td>
<td>States of the system</td>
</tr>
<tr>
<td>Cost</td>
<td>Energy</td>
</tr>
<tr>
<td>Control variables</td>
<td>Temperature</td>
</tr>
<tr>
<td>Final Solution</td>
<td>Frozen state</td>
</tr>
</tbody>
</table>

The initial design vectors of simulated annealing are randomly selected. Uphill
moves are occasionally allowed in order to escape from the local optimum value. For
example, searching for the minimum value in the curve of \( f(x) = x \cdot \sin(x) \) within the
range of \( x \in [-6, 6] \), as portrayed in Fig. 2.1. Suppose the initial guess position is at B.
Since traditional optimization methods only permit downhill moves, the next step may be
C, then D, and finally converges at A. While in simulated annealing, uphill moves are
allowed in some iterations, so the solution is possible to jump from C to F and eventually find the another local optimal value at E. This sequence of event is repeated until SA finds to the global optimum.

Figure 2.1 Local Minimum Value versus Global Minimum Value

The stopping criteria of SA vary for different problems. The optimization process could be stopped if a given minimum value is obtained, a certain number of iterations are conducted, or no obvious improvement is achieved after some iterations.

A flow chart of the simulated annealing is shown in Fig. 2.2. The selection of parameter $\beta$ is the crux of the simulated annealing algorithm. $\beta$ determines the acceptance rate of uphill steps and it is related to the Boltzmann probability distribution and the
temperature. If the value of $\beta$ is too big, the potential solution may not have enough energy to escape from the local optimum. Conversely, if $\beta$ is too small, the solution will wander all over the searching space.

Choose starting design $X_0$

Calculate the fitness value $f_0$

Randomly select a point on the surface of a unit $n$-dimensions to get a search direction $S$

Use step size $a$, Calculate $f_1=f(x_0+aS)$

Calculate $\Delta f=f_1-f_0$

$\Delta f \leq 0$

Yes

$p=e^{-\beta \times \Delta f}$

$r=\text{rand}()$

$r \leq p$

Yes

The step is accepted and the design vector is updated

No

$p=1$

$r=\text{rand}()$

$r \leq p$

No

Design vector remain unchanged

Yes

Figure 2.2 Flow Chart of the Simulated Annealing
2.2 Genetic Algorithm

The idea of genetic algorithm (GA) comes from imitating natural evolutionary processes. Chromosomes are equivalent to the solutions, the initial population corresponds to the initial design vectors of the first generation, and the fitness value represents the evaluation of the solutions. Two types of genetic operators, crossover, and mutation, define the methods of generating new populations. Immigrants are randomly generated population to keep the diversity of the group [19].

Table 2.2 GA Terminologies

<table>
<thead>
<tr>
<th>Biological</th>
<th>Genetic Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromosome</td>
<td>Possible solutions</td>
</tr>
<tr>
<td>Population</td>
<td>A group of solutions</td>
</tr>
<tr>
<td>Allele</td>
<td>Piece of the design vector</td>
</tr>
<tr>
<td>Locus</td>
<td>The position of the allele in chromosome</td>
</tr>
<tr>
<td>Fitness</td>
<td>Evaluation of possible solutions</td>
</tr>
<tr>
<td>Crossover</td>
<td>Allele exchange between parents</td>
</tr>
<tr>
<td>Mutation</td>
<td>Replacement of a random element in design vector with a random value</td>
</tr>
</tbody>
</table>

Three of the most crucial operations in the genetic algorithm are selection, crossover, and mutation. The details of these three operations are introduced as below.
2.2.1 Selection

The goal of the selection is to select the “well-behaved” individuals from the current population and to give them more opportunities to reproduce their children.

![Selection Operation](image)

The selection operation is based on the fitness value of the individuals with specific standards. The standards vary from different problems. Those solutions that are more accord with the standards will have a higher probability to be selected, but not decisive. The theory of selection reflects the principle of Darwin's survival of the fittest.

2.2.2 Crossover

Crossover is another important genetic algorithm operator. Most of the new individuals in the next generation are generated through crossover operation. The child chromosome will inherit characteristics from both of its parents.

![Crossover Operation](image)
Every individual has a chance to randomly crossover with other individuals within a population. For a single individual, the probability of exchanging part of its chromosome with other individuals is called crossover rate. Papers [20-21] suggest that using more than two parent chromosomes to participate in crossover operation would achieve a better solution. Crossover operation embodies the idea of information exchange.

2.2.3 Mutation

Mutation operation randomly selected a group of individuals at the beginning of the search. The selected individuals would have a certain probability of changing one or more gene values in its chromosome. The mutation rate is tiny. However, it is crucial to keeping the diversity of the population.

![Figure 2.5 Mutation Operation](image)

After these three operations, a new generation of chromosomes will be produced. Since the “well-behaved” chromosomes have more chance to breed their children chromosomes, the chromosomes in the new generations are expected to move towards the best solutions [22]. Although the relatively “bad-behaved” chromosomes may be less accord with the standards, they still contribute to the diversity of the groups. A flow chart of the genetic algorithm is illustrated in Fig. 2.6.
Figure 2.6 Flow Chart of the Genetic Algorithm

2.3 Particle Swarm Optimization

Particle Swarm Optimization (PSO) was developed by J. Kennedy and R. Eberhart in 1995 [23]. It was originally used for solving continuous nonlinear functions. The idea of PSO comes from a simplified social system like bird flocking or fish schooling.
Imagine a group of birds is searching for food in an n-dimensional area (n equals the number of control variables). None of these birds knows where the food is. However, they know which bird is nearest to the food (assume the closest bird to the food is Bird A). The best strategy for the rest of birds to find the food is following Bird A and searching its neighboring area.

In PSO, each single solution (particle) can be viewed as a "bird". The position of each particle can be expressed as $x_i = (x_{i1}, x_{i2}, ..., x_{in})$. The initial solutions in PSO are randomly selected and then PSO will continually search for optimal value by updating the solutions in each iteration. The fitness value of the particle is related to the objective function. And the velocity of the particles $v_i = (v_{i1}, v_{i2}, ..., v_{in})$ is related to its previous velocity, global best known position, and local best known position. The velocity indicates the directions of all the particles in the next iteration. The local best known position is the best solution that achieved by each particle so far. The global best known position is the best solution among all the achieved solutions. The inertia velocity part, local best known position part, and global best known position part of the velocity reflect the cooperation and competition mechanism in PSO.

Similar to GA, PSO also starts with a group of randomly generated solutions and updates the solutions in each iteration. However, PSO uses historical data rather than does crossover and mutation operations. The behavior of all the particles appears to be managed by a control center. However, in reality, as formula 2.1 and formula 2.2 describe below, the principle of the PSO algorithm is quite straightforward.

$$v_{d+1} = k \cdot (w \cdot v_d + \varphi_1 \cdot rand() \cdot (p_{best} - x_d) + \varphi_2 \cdot rand() \cdot (g_{best} - x_d))$$  \hspace{1cm} (2.1)
\[ x_{d+1} = x_d + v_{d+1} \]  \hfill (2.2)

where \( w \) is the inertia weight factor,

\( \phi_1 \) and \( \phi_2 \) are acceleration factors,

\( \text{rand}() \) is a random value between 0 and 1.

\( k \) is the constriction factor.

The acceleration factors handle the step sizes of the particles in the next iteration. If the acceleration factors are too small, the particles may not have enough velocity to reach the target regions. If the acceleration factors are too big, the particles may fly over the optimal value. Appropriate selection of acceleration factors could avoid trapping into local minimal and reduce the computation time.

\( V_{\text{max}} \) limits the maximum velocity of each particle. If the velocity of a particle is greater than maximum allowable velocity, then the velocity of that particle will be limited to \( V_{\text{max}} \). Otherwise, the particle may also fly over the optimal solution. The maximum velocity is specified by users depending on different problems.

The advantages of PSO is summarized in [24]:

1. PSO choose the directions of next step by cooperation and competition.

2. Fewer parameters need to be set compared to simulated annealing method and genetic algorithm method.

3. The computation speed of PSO is less sensitive to the complexity of the objective functions.

4. PSO algorithm applies to many fields.

The flow chart of the PSO algorithm is shown in fig. 2.7.
Randomly generate the location of each particle

Randomly generate the velocity of each particle

Evaluate the objective function value at each particle

Set $G_{\text{best}}$ and $P_{\text{best}}$

Update the velocity of each particle

$V_i \leq V_i^{\text{max}}$

Yes $V_i = V_i^{\text{max}}$

No $X_{dt+1} = X_d + V_d$

Evaluate the objective function value at each particle

$Val_i \leq Val_{P_{\text{best}}}$

Yes $Val_{P_{\text{best}}} = Val_i$, $P_{\text{best}} = P_{i+1}$

No $G_{\text{best}} = \min(P_{\text{best}})$

Stopping criteria met

Yes Results

No

Figure 2.7 Flow Chart of the Particle Swarm Optimization
2.3.1 Difference between GA and PSO

In genetic algorithm, the communication scheme is bidirectional, chromosomes could share information with each other. However, the communication scheme is one-way in PSO. Only the global best-known position could send its information to the other particles. Another difference is that the concepts in PSO are very clear. PSO does not need to do encoding and transform the original solution into binaries, and then do decoding at the end of the search, thus making it much easier to understand.

2.3.2 PSO Parameters Selection

The selection of the PSO parameters for general problems is listed in Table 2.3. Programmers may change some of these parameters based on different problems.

Table 2.3 PSO Parameters Selection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size</td>
<td>20-40 works well for most of the optimization problems.</td>
</tr>
<tr>
<td></td>
<td>However, as the dimension increase, the number of the particle should also increase according.</td>
</tr>
<tr>
<td>Dimension of the particles</td>
<td>Equals the number of control variables.</td>
</tr>
<tr>
<td>Domains of the particles</td>
<td>Depends on the upper bound and lower bound constraints</td>
</tr>
<tr>
<td>Acceleration factor</td>
<td>$2 \leq \phi_1 = \phi_2 \leq 4$</td>
</tr>
<tr>
<td>Stopping criteria</td>
<td>Iteration number</td>
</tr>
<tr>
<td></td>
<td>Difference between the current best solution and the previous best solution</td>
</tr>
<tr>
<td></td>
<td>No improvement after a certain number of iterations</td>
</tr>
</tbody>
</table>
Chapter Three: Reactive Power Dispatch Problem Formulation

The loads in the power system keep changing all the time. In order to maintain the power system operating at the timely optimum state, the reactive power optimization need be continuously conducted in theory. However, frequent switching operations are not feasible in the practical application. These operations will not only bring extra workload to the operator of the network, but also accelerate the aging of the equipment in the power systems. Sometimes the frequent switching operations may even threaten the safety operation of the network. Therefore, the number of switching operations and tap positions changing operations are strictly limited.

Most of the existing models convert the dynamic model into the static model. [25-26] suggest to divide a whole day into several intervals and then further divide each interval into several periods. Within each of these periods, the discrete control variables remain constant. Only the continuous control variables keep changing to reduce the power loss. The minimum real power loss during a day is set as the optimization object. The advantage of this method is that it can reduce the total power loss of the system while significantly decrease the number of switching operations.

Relying on the load forecasting and wind speed prediction information, grid operators can obtain the solutions of the reactive power dispatch at different wind conditions in advance, and then match these solutions with the real situations to minimize the real power loss.
3.1 Objective Function

Reactive power dispatch in power systems may have different goals. It can be minimizing the real power loss, getting the best voltage quality, using minimum capacitors or achieving maximum economic profit. In this thesis, the goal of the reactive power dispatch is to get the minimum real power loss.

The real power loss of the system equals the sum of the real power loss on each branch, and it can be described as:

\[ f : P_{\text{loss}} = \sum_{k=1}^{N} \left( V_{i}^2 + V_{j}^2 - 2V_{i}V_{j} \cos \theta_{ij} \right) \]  

(3.1)

where \( N \) is the number of the branches,

\( g_{ij} \) is the conductance of the branch between bus \( i \) and bus \( j \),

\( V_{i} \) is the voltage magnitude of bus \( i \),

\( V_{j} \) is the voltage magnitude of bus \( j \),

\( \theta_{ij} \) is the difference of phase angle between bus \( i \) and bus \( j \).

3.2 Constraints

Reactive power dispatch problem has both equality constraints and inequality constraints to process.

3.2.1 Equality Constraints

The equality constraints are the power balance equations, which can be described by the equations below:

\[ h_1 : P_{gi} - P_{di} - V_i \sum_j V_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) = 0 \]  

(3.2)

\[ h_2 : Q_{gi} - Q_{di} - V_i \sum_j V_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) = 0 \]  

(3.3)
where $P_{gi}$ is the real power generation at bus $i$,

$P_{di}$ is the real power demand at bus $i$,

$Q_{gi}$ is the reactive power generation at bus $i$,

$Q_{di}$ is the reactive power demand at bus $i$.

### 3.2.2 Inequality Constraints

The inequality functions are the ranges of the voltage magnitudes, tap positions of the transformers, and reactive power injection. Some of the parameters are continuous, as the voltage magnitudes. While some are discrete, like the tap positions of the transformers and reactive power injection. The commonly used method to manage the discrete values is viewing them as continuous values at the beginning of the optimization and then mapping the continuous values back to the discrete values in the end. In this thesis, the discrete variables are seen as continuous variables initially and then keep three decimal places at the end of the search.

\[
g_1 : V_{i}^{\text{min}} < V_i < V_{i}^{\text{max}} \quad (3.4) \\
g_2 : t_{j}^{\text{min}} < t_j < t_{j}^{\text{max}} \quad (3.5) \\
g_3 : Q_{gi}^{\text{min}} < Q_{gi} < Q_{gi}^{\text{max}} \quad (3.6)
\]

Based on the original parameters in IEEE 14 bus system, the range of voltage magnitude in this thesis is set from 0.95 p.u. to 1.10 p.u. The range of the tap position is set from 0.975 to 1.025. The reactive power injection of the compensators is set between 0 MVar to 20 MVar.
3.3 Exterior Penalty Function (EPF) Method

Reactive power dispatch problem is a constrained problem. In optimization, the constrained problems are usually converted into unconstrained problems for convenience. One of the commonly used methods to convert the constrained problem is adding exterior penalty function terms to the objective function [27], which is also known as exterior penalty function method, as represent in the formula 3.7.

\[
\text{Minimize: } F : f + P(X, r_h, r_g) = \min_{x'} \{ x' \mid x' \leq x'' \}
\]

where \( P(r_h, r_g) \) is the penalty function,

- \( r_h \) is the penalty multiplier for the equality constraint.
- \( r_g \) is the penalty multiplier for the inequality constraint.

\( F \) is called the augmented function. [28]

The equality constraint in this thesis will be automatically fulfilled by using MATPOWER 5.1 toolbox, so only inequality constraints need to be concerned. Therefore, the final objective function could be described as:

\[
F = P_{loss} + \sum q \left( V_i - V_i^{\text{lim}} \right)^2 + \sum r_h \left( T_i - T_i^{\text{lim}} \right) + \sum r_g \left( Q_i - Q_i^{\text{lim}} \right)^2,
\]

where

\[
V_i^{\text{lim}} = \begin{cases} \max_i \mid V_i > V_i^{\text{max}} \\ \min_i \mid V_i < V_i^{\text{min}} \end{cases}
\]

\[
T_i^{\text{lim}} = \begin{cases} \max_i \mid T_i > T_i^{\text{max}} \\ \min_i \mid T_i < T_i^{\text{min}} \end{cases}
\]

\[
Q_i^{\text{lim}} = \begin{cases} \max_i \mid Q_i > Q_i^{\text{max}} \\ \min_i \mid Q_i < Q_i^{\text{min}} \end{cases}
\]
In EPF, if all the control variables are within the limits, the penalty function terms would be zero. On the contrary, if the control variables exceed the limits, then the penalty function terms would be added to the objective function to penalize the violation. The penalty multipliers are always assigned big numbers in programming. When the penalty multipliers keep increasing until approaching infinity, the constrained problem will transform to the unconstrained problem. In reactive power dispatch, if the control variables exceed the voltage limit, significant damages to the power systems would occur. So the voltage magnitudes, tap positions, and reactive power injection have to be carefully examined.

3.4 MATPOWER

In this thesis, MATPOWER 5.1 toolbox is introduced to calculate the power flow and to fulfill the equality constraints.

MATPOWER is a pack of MATLAB M-files that is developed by Ray D. Zimmerman, Carlos E. Murillo-Sánchez and Deqiang Gan in 1996 to meet the computational requirements of the PowerWeb project [29]. In order to install the MATPOWER 5.1 toolbox, MATLAB version 7 or later is suggested as a system requirement. The biggest advantages of MATPOWER is its easiness to use and modify the original code. Furthermore, MATPOWER is open source and posted for free, users can download the toolbox at:

http://www.pserc.cornell.edu/matpower/

In this section, several useful input and output MATPOWER functions related to this thesis are presented.
3.4.1 The loadcase Function

The loadcase function can load the case information from the struct, M-file or MAT-file. The imported information is then saved in a struct. Users can change the structure of the network by modifying the imported data when needed.

The standard format of using loadcase is: mpc = loadcase(casefile)

3.4.2 The savecase Function

The savecase function can save the information of the network to M-file or MAT-file. These files can also be overwritten in case of need. In MATLAB 7.10 environment, if the case file needs to be overwritten more than once in a single run, users need to choose saving the case information in MAT-format. Otherwise, an error message would appear, and the case information would remain unchanged.

The standard format of using savecase is: savecase(fname, mpc).

3.4.3 The runpf Function

The runpf function can calculate the power flow of the network. When calculating the power flow, the runpf function has several different options. ‘NR’ refers to using Newton’s method, ‘FDXB’ is the fast decoupled method, and ‘GS’ means using Gauss-Seidel method. ‘AC’ is calculating the AC power flow of the system, and ‘DC’ is calculating the DC power flow of the system. By default, runpf works at the AC power flow mode and uses Newton Raphson’s method to compute the power flow.

The standard format of using runpf is: results = runpf(casedata).
3.4.4 The get_losses Function

The get_losses function can calculate the reactive power injection and power loss in all branches, by using the following formulas.

\[ loss_i = \frac{|v_f^{\text{ref}_\text{shift}} - v_i|}{r_s - jx_s}^2 \]  
(3.13)

\[ f_{chg} = \left| \frac{v_f^{\text{ref}_\text{shift}}}{2 b_c/2} \right| \]  
(3.14)

\[ t_{chg} = |v_t|^2 \frac{b_c}{2} \]  
(3.15)

The standard format of using get_losses function is loss = get_losses(results).

3.4.5 Canonical Form of the Generator Information

The canonical form of the generator information in MATPOWER 5.1 is:

\[ \text{[gen_bus, Pg, Qg, Qmax, Qmin, Vg, Mbase, status, Pmax, Pmin, pc1, pc2, qe1min, qe1max, qe2min, qe2max, ramp_agc, ramp_10, ramp_30, ramp_q, apf]} \].

The parameters settings of the generator data in IEEE 14 bus system are presented in fig. 3.1, and some of the most important generator name columns and their corresponding meanings are listed in Table 3.1.

Figure 3.1 Canonical Form of the IEEE 14 Bus System Generator Data
Table 3.1 Explanation of the Generator Name Columns

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen_bus</td>
<td>Bus number of the generator</td>
</tr>
<tr>
<td>Pg</td>
<td>Real power generation</td>
</tr>
<tr>
<td>Qg</td>
<td>Reactive power generation</td>
</tr>
<tr>
<td>Qmax</td>
<td>Maximum reactive power output</td>
</tr>
<tr>
<td>Qmin</td>
<td>Minimum reactive power output</td>
</tr>
<tr>
<td>Vg</td>
<td>Voltage magnitude of the bus</td>
</tr>
<tr>
<td>Pmax</td>
<td>Maximum real power output</td>
</tr>
<tr>
<td>Pmin</td>
<td>Minimum real power output</td>
</tr>
</tbody>
</table>

3.4.6 Canonical Form of the Branch Information

The canonical form of the branch information in MATPOWER 5.1 is: [f_bus, t_bus, br_r, br_x, br_b, rate_a, rate_b, rate_c, ratio, angle, angmin, angmax]. The parameters settings of the branch data in the IEEE 14 bus system are presented in fig. 3.2. Some of the most important branch name columns and their corresponding meanings are listed in Table 3.2.
Table 3.2 Explanation of the Branch Name Columns

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_bus</td>
<td>From bus number</td>
</tr>
<tr>
<td>t_bus</td>
<td>To bus number</td>
</tr>
<tr>
<td>br_r</td>
<td>Resistance of the branch</td>
</tr>
<tr>
<td>br_x</td>
<td>Reactance of the branch</td>
</tr>
<tr>
<td>rate_a</td>
<td>Long-term rating of the branch</td>
</tr>
<tr>
<td>rate_b</td>
<td>Short-term rating of the branch</td>
</tr>
<tr>
<td>rate_c</td>
<td>Emergency rating of the branch</td>
</tr>
</tbody>
</table>
### 3.4.7 Canonical Form of the Bus Information

The canonical form of the bus information in MATPOWER 5.1 is [bus_i, bus_type, Pd, Qd, gs, bs, area, Vm, Va, base_kv, zone, Vmax, Vmin]. The parameters settings of the bus data in the IEEE 14 bus system are presented in fig. 3.3. Some of the most important bus name columns and their corresponding meanings are listed in Table 3.3.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Tap ratio of the transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>Phase shift angle of the transformer</td>
</tr>
<tr>
<td>Pf</td>
<td>Real power injection at “from” bus side</td>
</tr>
<tr>
<td>Qf</td>
<td>Reactive power injection at “from” bus side</td>
</tr>
<tr>
<td>Pt</td>
<td>Real power injected at “to” bus side</td>
</tr>
<tr>
<td>Qt</td>
<td>Reactive power injected at “to” bus side</td>
</tr>
</tbody>
</table>

Figure 3.3 Canonical Form of the IEEE 14 Bus System Bus Data

32
Table 3.3 Explanation of the Bus Name Columns

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus_i</td>
<td>Bus number</td>
</tr>
<tr>
<td>Bus-type</td>
<td>1 means PQ bus, 2 means PV bus, and 3 means slack bus</td>
</tr>
<tr>
<td>Pd</td>
<td>Real power load</td>
</tr>
<tr>
<td>Qd</td>
<td>Reactive power load</td>
</tr>
<tr>
<td>Gs</td>
<td>Shunt conductance</td>
</tr>
<tr>
<td>Bs</td>
<td>Shunt susceptance</td>
</tr>
<tr>
<td>Area</td>
<td>Bus area</td>
</tr>
<tr>
<td>Vm</td>
<td>The magnitude of the voltage</td>
</tr>
<tr>
<td>Va</td>
<td>The phase angle of the voltage</td>
</tr>
<tr>
<td>Zone</td>
<td>Zone number</td>
</tr>
</tbody>
</table>

3.5 Procedures of the PSO Based Reactive Power Dispatch

To conclude, the main optimization steps of the PSO based reactive power dispatch are as follows:

1. Load case information: in MATPOWER, IEEE 14 bus system data is saved in case14.m file. Users can also create their personalized case by following the format of the canonical forms of generators, buses, and branches.

2. Initialization: set the total iteration number, particle number, and initial velocity, randomly assign the position of each particle in the design space. Then evaluate
the fitness of each particle and save the global best-known position, and the local
best-known position of each particle.

3 Update the positions and velocities: updating the position and velocity of each particle by using formula 2.1 and formula 2.2. Then check whether the solution violates the limit or not. If the solution exceeds the limits, use the EPF method to penalize the violations.

4 Evaluate each particle: substitute the position of each particle into the objective function to calculate the evaluation value.

5 Update local best-known position: if the current fitness value is smaller than the historical best fitness value, update the local best-known position.

6 Update global best-known position.

7 Decide stopping criterion: determine if the iteration has reached the maximum iteration number. If so, stop the optimization process and print the result; otherwise, iter=iter+1, and go back to step 3.

The flow chart of the PSO based reactive power dispatch is illustrated in the Fig. 3.4.
Randomly generate the location of each particle

Randomly generate the velocity of each particle

Evaluate the objective function value at each particle

Set Gbest and Pbest

Update the velocity of each particle

\[ V_i \leq V_{i}^{\text{max}} \]

\[ V_{i} = V_{i}^{\text{max}} \]

No

\[ W_{d+1} = W_{d} + V_{d} \]

Evaluate the objective function value at each particle

Control variable within limit

Penalize

Yes

Val \leq Val_{P_{\text{best}}} \rightarrow Val_{P_{\text{best}}} = Val_{i}, P_{\text{best}} = P_{i+1}

No

Val_{\text{best}} = \min(P_{\text{best}})

Stopping criteria met

Yes

Results

Figure 3.4 Flow Chart of the PSO Based Reactive Power Dispatch
Chapter Four: Case Studies

4.1 IEEE 14 Bus System Data

The performance of the proposed method is verified on IEEE 14 bus system. The structure of the 14 buses network is shown in Fig. 4.1 [30].

There are two generators in the IEEE 14 bus system. One is at the slack bus; the other one is at bus 2. Three synchronous condensers are located at bus 3, bus 6, and bus 8, respectively. There are also three transformers and one shunt reactive power compensator.
in this system. The total real power load is 259 MW and the total reactive power load is 73.5 MVar. Other detail information of this system is listed as below:

Table 4.1 IEEE 14 Bus System Loads Parameters

<table>
<thead>
<tr>
<th>Load</th>
<th>Bus number</th>
<th>P (MW)</th>
<th>Q (MVar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>21.7</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>94.2</td>
<td>19.0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>47.8</td>
<td>-3.9</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>7.6</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>11.2</td>
<td>7.5</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>29.5</td>
<td>16.6</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>9.0</td>
<td>5.8</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>6.1</td>
<td>1.6</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>13.5</td>
<td>5.8</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>14.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 4.2 IEEE 14 Bus System Generators Parameters

<table>
<thead>
<tr>
<th>Generator number</th>
<th>Bus type</th>
<th>Voltage (p.u.)</th>
<th>P (MW)</th>
<th>Q (MVar)</th>
<th>Maximum Q</th>
<th>Minimum Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slack</td>
<td>1.060</td>
<td>232.4</td>
<td>-16.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>PV</td>
<td>1.045</td>
<td>40</td>
<td>42.4</td>
<td>50</td>
<td>-40</td>
</tr>
<tr>
<td>3</td>
<td>PV</td>
<td>1.010</td>
<td>0</td>
<td>23.4</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>From Bus</td>
<td>To Bus</td>
<td>R</td>
<td>X</td>
<td>B</td>
<td>Tap Position</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>PV</td>
<td>1.070</td>
<td>0</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>PV</td>
<td>1.090</td>
<td>0</td>
<td>17.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 IEEE 14 Bus System Branches Parameters
The MATLAB code for the reactive power dispatch without adding new DGs is attached in Appendix A. Most of the time, there would be no obvious improvement on the optimization result after conducting one hundred iterations. But in order to give the particles enough opportunities to reach the global minimum, the stopping criteria of the optimization process is set as the iteration number reaching two hundred. The size of the swarm is fifty. The initial weight inertia is set as 0.9, and the final weight inertia is set as 0.4. As the iterations go on, the weight value will drop from 0.9 to 0.4. The position of each particle is defined in a nine-dimensional space, as shown in Fig. 4.2:

\[
\begin{array}{cccccccc}
V_1 & V_2 & V_3 & V_6 & V_8 & T_1 & T_2 & T_3 & S_9 \\
\end{array}
\]

Figure 4.2 Coordinates of the Particle

In Fig. 4.2, \( V \) represents the voltage magnitudes at the slack bus or PV bus, \( T \) is for the tap position of the transformer, and \( S_9 \) is the reactive power injection at bus 9.

### Table 4.4 IEEE 14 Bus System Reactive Power Injection Parameter

<table>
<thead>
<tr>
<th>Bus number</th>
<th>Reactive Power Injection (MVar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9</th>
<th>14</th>
<th>0.12711</th>
<th>0.27038</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>11</td>
<td>0.08205</td>
<td>0.19207</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>0.22092</td>
<td>0.19988</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>0.17093</td>
<td>0.34802</td>
<td>0</td>
</tr>
</tbody>
</table>
When the optimization process starts, the position of each particle will be continuously updated until reaching the stopping criteria.

Fig. 4.3 shows the optimization process of reactive power dispatch without installing new DG. At the beginning of the optimization process, the positions of the particles are randomly selected. The global optimal real power loss is about 13.5 MW at that time. As the particles continually update their positions towards the best solution, the real power loss keeps decreasing. After 100 iterations, no obvious improvement can be observed. Finally, the active power loss converges to 12.36 MW.

![Figure 4.3  Loss Reduction Process](image-url)
Table 4.5 shows the real power loss on each branch before and after the particle swarm optimization. Even though the active power loss in some branches are slightly increased, (for instance, branch 6-12, 6-13, 9-14), the overall real power loss of the 14 buses system is significantly reduced.

Table 4.5 Comparison of the Real Power Loss at Each Branch

<table>
<thead>
<tr>
<th>Branch number</th>
<th>Before optimization (MW)</th>
<th>After optimization (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>4.298</td>
<td>3.907</td>
</tr>
<tr>
<td>1-5</td>
<td>2.763</td>
<td>2.552</td>
</tr>
<tr>
<td>2-3</td>
<td>2.323</td>
<td>2.147</td>
</tr>
<tr>
<td>2-4</td>
<td>1.677</td>
<td>1.546</td>
</tr>
<tr>
<td>2-5</td>
<td>0.904</td>
<td>0.828</td>
</tr>
<tr>
<td>3-4</td>
<td>0.373</td>
<td>0.347</td>
</tr>
<tr>
<td>4-5</td>
<td>0.514</td>
<td>0.462</td>
</tr>
<tr>
<td>4-7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4-9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5-6</td>
<td>0</td>
<td>0</td>
</tr>
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<td>7-9</td>
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</table>
4.3 Reactive Power Dispatch with a New DG Operating at Rated Power

The second case study is about adding a new DG to the IEEE 14 bus system and then optimizes the reactive power of the system by using PSO. Wind generator, solar panels, and micro-turbine can all be chosen as an alternative of DG. In this thesis, Enercon E82 wind turbine is selected as the new DG. Enercon E82 is a direct-drive synchronous generator. Its rated power is 2000 kW. The wind generator is assumed to operate at its rated power in the second case study.

In the next page, the shaded area in Fig. 4.4 describes reactive power capability of Enercon E82 [31]. When the real power output is 0 MW, the wind generator can still deliver as much as 1.2 MVar or absorb -1.0 MVar reactive power. Since 2007, some commercial wind turbines have already been equipped with this kind of full reactive power capability, which can produce full reactive power regardless of the wind conditions. While the reactive power capacity of the early products is usually related to their real-time real power outputs.
Figure 4.4 Reactive Power Capacity of Enercon E82 (2010 FACTS-WT)

Figure 4.5 Reactive Power Capacity of Enercon E66 (2002)
In order to apply the MATLAB code in the previous section into this case study, several parameters need to be modified before executing the MATLAB code.

If the wind turbine is installed on a PV bus (e.g. bus 2), then both real and reactive power capacity of the generator need to be changed. In Fig. 4.6, note that the active power output of the generator at bus 2 is increased from 40 to 42.2, the range of reactive power output is changed from [-40, 50] to [-41, 51.2].

```
%% generator data
% The Qmax at bus 1 has been changed to 0 since it is slack bus
%% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin Pcl Pc2 Qclmin Qclmax Qc2min Qc2max
spc.gen = [
    1 232.4 -16.9 0 0 1.06 100 1 332.4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    2 42.05 42.4 51.2 -41 1.045 100 1 140 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    3 0 23.4 40 0 1.01 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    5 0 12.2 24 -6 1.07 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    8 0 17.4 24 -6 1.09 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
];
```

Figure 4.6 Generator Data of the Modified System when the DG is Installed on Bus 2

Similar changes will also be performed in other cases, as shown in the graphs from Fig. 4.7 to Fig. 4.9.

```
%% generator data
% The Qmax at bus 1 has been changed to 0 since it is slack bus
%% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin Pcl Pc2 Qclmin Qclmax Qc2min Qc2max
spc.gen = [
    1 232.4 -16.9 0 0 1.06 100 1 332.4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    2 0 40 42.4 50 1.045 100 1 140 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    3 2.05 23.4 41.2 -1 1.01 100 1 102.05 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    6 0 12.2 24 -6 1.07 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    8 0 17.4 24 -6 1.09 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
];
```

Figure 4.7 Generator Data of the Modified System when the DG is Installed on Bus 3

44
The position of each particle, in this case, will remain the same as in the previous section. The MATLAB code in Appendix A can still be used to solve the optimal reactive power dispatch problem in this case.

Figure 4.10 Coordinates of the Particle when the New DG is connected to a PV Bus

If the wind turbine is installed on PQ bus (e.g. bus 4), in addition to modifying the capacity of the real and reactive power to new parameters, the voltage magnitude of the new installed DG bus should also be treated as a new control variable, as illustrated in the fig. 4.11.
Figure 4.11 Coordinates of the Particle when the New DG is on a PQ Bus

where \( V_r \) represents the voltage magnitude of the new DG.

The MATLAB code in Appendix A will not be fit for this case. So the MATLAB code in Appendix B is used for solving the reactive power dispatch problem. The differences between the two codes are highlighted in the Appendix B. Other changes on the bus data and generator data are presented in the graphs from fig. 4.12 to fig. 4.29.

<table>
<thead>
<tr>
<th>% bus data</th>
</tr>
</thead>
<tbody>
<tr>
<td>% bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax Vmin</td>
</tr>
<tr>
<td>mpc.bus = [</td>
</tr>
<tr>
<td>1 3 0 0 0 0 1 1.06 0 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>2 2 21.7 12.7 0 0 1 1.045 -4.98 0 1 1.06 0.94;</td>
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<tr>
<td>3 2 94.2 19 0 0 1 1.01 -12.72 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>4 2 47.8 -3.9 0 0 1 1.019 -10.33 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>5 1 7.6 1.6 0 0 1 1.02 -8.78 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>6 2 11.2 7.5 0 0 1 1.07 -14.22 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>7 1 0 0 0 0 1 1.062 -13.37 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>8 2 0 0 0 0 1 1.09 -13.36 0 1 1.06 0.94;</td>
</tr>
<tr>
<td>9 1 29.5 16.6 0 19 1 1.056 -14.94 0 1 1.06 0.94;</td>
</tr>
<tr>
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</tr>
<tr>
<td>11 1 3.5 1.8 0 0 1 1.057 -14.79 0 1 1.06 0.94;</td>
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<tr>
<td>12 1 6.1 1.6 0 0 1 1.055 -15.07 0 1 1.06 0.94;</td>
</tr>
<tr>
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</tr>
<tr>
<td>14 1 14.9 5 0 0 1 1.036 -16.04 0 1 1.06 0.94;</td>
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</table>

Figure 4.12 Bus Data of the Modified System when the DG is Installed on Bus 4

In the generator data section of the modified 14 bus system, the parameters of the new generator are added.
Figure 4.13 Generator Data of the Modified System when the DG is Installed on Bus 4

Similar changes are needed before executing the MATLAB code to calculate the reactive power dispatch problems at the buses.

Figure 4.14 Bus Data of the Modified System when the DG is Installed on Bus 5
Figure 4.15 Generator Data of the Modified System when the DG is Installed on Bus 5

![Generator Data Table]

Figure 4.16 Bus Data of the Modified System when the DG is Installed on Bus 7

![Bus Data Table]
Figure 4.17 Generator Data of the Modified System when the DG is Installed on Bus 7

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<th>Vg</th>
<th>aBase</th>
<th>status</th>
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<th>Pmin</th>
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<th>Pc2</th>
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Figure 4.18 Bus Data of the Modified System when the DG is Installed on Bus 9

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Figure 4.19 Generator Data of the Modified System when the DG is Installed on Bus 9

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<th>P_{min}</th>
<th>P_{c1}</th>
<th>P_{c2}</th>
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Figure 4.20 Bus Data of the Modified System when the DG is Installed on Bus 10

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<td>-14.94</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
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<td>0</td>
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<td>-15.1</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
</tr>
<tr>
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<td>1.8</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.057</td>
<td>-14.79</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
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<td>-15.07</td>
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<td>1.036</td>
<td>-16.04</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
</tr>
</tbody>
</table>
**Figure 4.21 Generator Data of the Modified System when the DG is Installed on Bus 10**

```
% generator data
% The Qmax at bus 1 has been changed to 0 since it is slack bus
% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin Pcl Pc2 Qclmin Qclmax Qc2min Qc2a
mpc.gen = [
    1 232.4 -16.9 0 0 1.06 100 1 332.4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    2 40 42.4 50 -40 1.045 100 1 140 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    3 0 23.4 40 0 1.01 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    5 4 12.2 24 -6 1.07 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    6 0 17.4 24 -6 1.05 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 2.05 0 1.2 -1 1.081 100 1 2.05 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
];
```

**Figure 4.22 Bus Data of the Modified System when the DG is Installed on bus 11**

```
% bus data
% bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax Vmin
mpc.bus = [
    1 3 0 0 0 0 1 1.06 0 0 1 1.06 0.94:
    2 2 21.7 12.7 0 0 1 1.045 -4.98 0 1 1.06 0.94:
    3 2 94.2 19 0 0 1 1.01 -12.72 0 1 1.06 0.94:
    4 1 47.8 -3.9 0 0 1 1.019 -10.33 0 1 1.06 0.94:
    5 1 7.6 1.6 0 0 1 1.02 -8.78 0 1 1.06 0.94:
    6 2 11.2 7.5 0 0 1 1.07 -14.22 0 1 1.06 0.94:
    7 1 0 0 0 0 0 1 1.062 -13.37 0 1 1.06 0.94:
    8 2 0 0 0 0 0 1 1.09 -13.36 0 1 1.06 0.94:
    9 1 29.5 16.6 0 0 0 1 1.056 -14.94 0 1 1.06 0.94:
    10 1 9 5.8 0 0 1 1.051 -15.1 0 1 1.06 0.94:
    11 2 3.5 1.8 0 0 1 1.057 -14.79 0 1 1.06 0.94:
    12 1 6.1 1.6 0 0 1 1.055 -15.07 0 1 1.06 0.94:
    13 1 13.5 5.8 0 0 1 1.05 -15.16 0 1 1.06 0.94:
    14 1 14.9 5 0 0 1 1.036 -16.04 0 1 1.06 0.94:
];
```
### % generator data

- **Figure 4.23 Generator Data of the Modified System when the DG is Installed on Bus 11**

<table>
<thead>
<tr>
<th>bus</th>
<th>Pg</th>
<th>Qg</th>
<th>Qmax</th>
<th>Qmin</th>
<th>Vg</th>
<th>mBase</th>
<th>status</th>
<th>Pmax</th>
<th>Pmin</th>
<th>Pcl</th>
<th>Pcl1min</th>
<th>Qclmax</th>
<th>Qcl1min</th>
<th>Qcl2min</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>322.4</td>
<td>-16.9</td>
<td>0</td>
<td>0</td>
<td>1.06</td>
<td>100</td>
<td>1</td>
<td>322.4</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>42.4</td>
<td>50</td>
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<td>1.045</td>
<td>100</td>
<td>1</td>
<td>140</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
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<td>0</td>
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<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>12.2</td>
<td>24</td>
<td>-6</td>
<td>1.07</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>17.4</td>
<td>24</td>
<td>-6</td>
<td>1.06</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| 11   | 2.05 | 0    | 1.2   | -1   | 1.057| 100   | 1      | 2.05 | 0     | 0    | 0        | 0      | 0       | 0       | 0     |

### % bus data

- **Figure 4.24 Bus Data of the Modified System when the DG is Installed on Bus 12**

```
mpc.bus = [  
1   3     0     0     0     0     1     1.06 | 0     0     1     1.06 | 0.94;
2   2     21.7  12.7  0     0     1     1.045| -4.98 | 0     1     1.06 | 0.94;
3   2     94.2  19    0     0     1     1.01 | -12.72| 0     1     1.06 | 0.94;
4   1     47.8  -3.9  0     0     1     1.019| -10.33| 0     1     1.06 | 0.94;
5   1     7.6   1.6   0     0     1     1.02 | -8.78 | 0     1     1.06 | 0.94;
6   2     11.2  7.5   0     0     1     1.07 | -14.22| 0     1     1.06 | 0.94;
7   1     0     0     0     0     1     1.062| -13.37| 0     1     1.06 | 0.94;
8   2     0     0     0     0     1     1.09 | -13.36| 0     1     1.06 | 0.94;
9   1     29.5  16.6  0     19    1     1.056| -14.94| 0     1     1.06 | 0.94;
10  1     9.8   5.8   0     0     1     1.051| -15.1 0     1     1.06 | 0.94;
11  1     3.5   1.8   0     0     1     1.057| -14.79| 0     1     1.06 | 0.94;
12  2     6.1   1.6   0     0     1     1.055| -15.07| 0     1     1.06 | 0.94;
13  1     13.5  5.8   0     0     1     1.05  | -15.16| 0     1     1.06 | 0.94;
14  1     14.9  5     0     0     1     1.036| -16.04| 0     1     1.06 | 0.94;
];
```
Figure 4.25 Generator Data of the Modified System when the DG is Installed on Bus 12

<table>
<thead>
<tr>
<th>bus</th>
<th>Pg</th>
<th>Qg</th>
<th>Qmax</th>
<th>Qmin</th>
<th>Yg</th>
<th>mBase</th>
<th>status</th>
<th>Pmax</th>
<th>Pmin</th>
<th>P0c1</th>
<th>P0c2</th>
<th>Q0c1min</th>
<th>Q0c1max</th>
<th>Q0c2min</th>
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</tr>
</thead>
<tbody>
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<td>232.4</td>
<td>-16.8</td>
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<td>0</td>
<td>1.06</td>
<td>100</td>
<td>1</td>
<td>332.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>42.4</td>
<td>50</td>
<td>-40</td>
<td>1.045</td>
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<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
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<td>-6</td>
<td>1.07</td>
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<td>0</td>
</tr>
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</tr>
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</table>

Figure 4.26 Bus Data of the Modified System when the DG is Installed on Bus 13

<table>
<thead>
<tr>
<th>bus_i</th>
<th>type</th>
<th>Pd</th>
<th>Qd</th>
<th>Gs</th>
<th>Bs</th>
<th>area</th>
<th>Vm</th>
<th>Va</th>
<th>baseKV</th>
<th>zone</th>
<th>Vmax</th>
<th>Vmin</th>
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</thead>
<tbody>
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<td>1</td>
<td>1.06</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>1.045</td>
<td>-4.98</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
<tr>
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<td>1.01</td>
<td>-12.72</td>
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<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
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<td>0</td>
<td>1.019</td>
<td>-10.33</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
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<td>0</td>
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<td>1.06</td>
<td>0.94</td>
</tr>
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<td>1.06</td>
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<td>1.06</td>
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<td>0</td>
<td>1.09</td>
<td>-13.36</td>
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<td>1.06</td>
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</tr>
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<td>9</td>
<td>5.8</td>
<td>0</td>
<td>0</td>
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<td>1.051</td>
<td>-15.1</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
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</tr>
<tr>
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<td>3.6</td>
<td>1.8</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.057</td>
<td>-14.79</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
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<td>6.1</td>
<td>1.6</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.055</td>
<td>-15.07</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
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</tr>
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<td>1.06</td>
<td>0.94</td>
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<td>-16.04</td>
<td>0</td>
<td>1</td>
<td>1.06</td>
<td>0.94</td>
</tr>
</tbody>
</table>
### Figure 4.27 Generator Data of the Modified System when the DG is Installed on Bus 13

```plaintext
%% generator data
% The Qmax at bus 1 has been changed to 0 since it is slack bus
% bus  Pg  Qg  Qmax  Gmin  Vg  nBase  status  Pmax  Pmin  Pcl  Qcl  Qc1min  Qc1max  Qc2min  Qc2max
mpc.gen = [
    1  232.4 -15.9  0  0  1.06  100  1  332.4  0  0  0  0  0  0  0  0  0  0  0  0  0
    2  40  42.4  50 -40  1.045  100  1  140  0  0  0  0  0  0  0  0  0  0  0  0  0
    3  0  23.4  40  0  1.01  100  1  100  0  0  0  0  0  0  0  0  0  0  0  0  0  0
    6  0  12.2  24 -6  1.07  100  1  100  0  0  0  0  0  0  0  0  0  0  0  0  0  0
    8  0  17.4  24 -6  1.09  100  1  100  0  0  0  0  0  0  0  0  0  0  0  0  0  0
    12  250  0  1.2 -1  1.08  100  1  2.08  0  0  0  0  0  0  0  0  0  0  0  0  0  0
];
```

### Figure 4.28 Bus Data of the Modified System when the DG is Installed on Bus 14

```plaintext
%% bus data
% bus_i  type  Pd  Qd  Gs  Bs  area  Vm  Va  baseKV  zone  Vmax  Vmin
mpc.bus = [
    1  3  0  0  0  0  0  1.06  0  0  1.06  0.94;
    2  2  21.7  12.7  0  0  0  1.045 -4.98  0  1.06  0.94;
    3  2  94.2  19  0  0  0  1.01 -12.72  0  1.06  0.94;
    4  1  47.8  -3.9  0  0  0  1.019 -10.33  0  1.06  0.94;
    5  1  7.6  1.6  0  0  0  1.02 -8.78  0  1.06  0.94;
    6  2  11.2  7.5  0  0  0  1.07 -14.22  0  1.06  0.94;
    7  1  0  0  0  0  0  1.062 -13.37  0  1.06  0.94;
    8  2  0  0  0  0  0  1.09 -13.36  0  1.06  0.94;
    9  1  29.5  16.6  0  0  0  1.056 -14.94  0  1.06  0.94;
    10  1  9  5.8  0  0  0  1.051 -15.1  0  1.06  0.94;
    11  1  3.5  1.8  0  0  0  1.057 -14.79  0  1.06  0.94;
    12  1  6.1  1.6  0  0  0  1.055 -15.07  0  1.06  0.94;
    13  1  13.5  5.8  0  0  0  1.05 -15.16  0  1.06  0.94;
    14  2  14.9  5  0  0  0  1.036 -16.04  0  1.06  0.94;
];
```
After running the MATLAB code, the real power loss of the system, when DG is installed on different buses, is shown in table 4.6 on the next page.

From the table, we can learn that the real power loss can be reduced by 7.89% by simply applying PSO algorithm. After adding a new DG to the system and using PSO algorithm to further adjusting the values of control variables, the real power loss can be reduced by as much as 10.27%. A comparison of the loss reduction, when DG is installed on different buses, is presented in Fig. 4.30.

Figure 4.29 Generator Data of the Modified System when the DG is Installed on Bus 14
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage at Bus 1</td>
<td>1.06 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10</td>
<td>1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10 1.10</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
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<td></td>
<td></td>
</tr>
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<td>Voltage at Bus 2</td>
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Table 4.7 shows the comparison of the real power loss of the original network, optimization without new DG, and optimization with new DG. We can learn that the real power loss on most of the branches is significantly reduced.

Table 4.7 Real Power Losses Comparisons

<table>
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<th>Branch #</th>
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<th>Optimization with DG</th>
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Fig. 4.31 shows the optimization process of the proposed method when the new wind turbine is installed on bus 3. The initial real power loss of the system is at about 12.45 MW. The particles start to converge after conducting eighty iterations. Finally, the total power loss of the system is 12.017 MW.
4.4 Reactive Power Dispatch with a New DG Operating at Various Power

In order to evaluate the performance of the proposed method at the various wind speed conditions, the third case study compares the power loss of the modified 14 bus system when the wind turbine delivers 25%, 50%, and 75% of its rated power, respectively.

The real power output curve of Enercon E82 wind turbine is presented in Fig. 4.32 [32]. When the wind speed is at 7 m/s, the output of the wind turbine is 532 W, which is about 25% of its rated power output. When the wind speed is about 9 m/s, the output of wind generator is 1.18 kW, approximately 50% of its rated power output. Finally, when
the wind speed is about 10 m/s, the output of the wind generator is 1.58 kW, about 75% of the rated power output.

When the wind speed is 7 m/s, the value of $P_g$ at bus 9 is changed to 532 W, as shown in fig. 4.33.

![Real Power Output Curve](attachment:image.png)

Figure 4.32 Real Power Output Curve of Enercon E82

When the wind speed is 7 m/s, the value of $P_g$ at bus 9 is changed to 532 W, as shown in fig. 4.33.

```
% generator data
% The Qmax at bus 1 has been changed to 0 since it is slack bus
% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin P1 P2 P3 P4 P5 P6
mpc.gen = [1 232.4 -16.9 0 0 1.06 100 1 332.4 0 0 0 0 0 0 0 0 0 0 0 0.1];
2 40 42.4 30 -40 1.045 100 1 140 0 0 0 0 0 0 0 0 0 0 0 0.1;
3 0 23.4 40 0 1.01 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0.1;
4 0 12.2 24 -6 1.07 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0.1;
5 0 17.4 24 -6 1.09 100 1 100 0 0 0 0 0 0 0 0 0 0 0 0.1;
6 0 532 0 1.2 -1.0 1.056 100 1 532 0 0 0 0 0 0 0 0 0 0 0.1;
7
8
9
```

Figure 4.33 Generators Data when the New Installed DG Delivers 25% Rated Power
The process of reactive power optimization, when DG produce 25% of its rated power output, is shown in fig. 4.34. Finally, the real power loss of the system converges at 12.1845 MW.

![Figure 4.34 Loss Reduction Process when DG Delivers 25% Rated Power](image)

**Table 4.8 Optimization Results when DG Deliver 25% Rated Power**

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<th>Control variable</th>
<th>Values</th>
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<td>Voltage at bus 2</td>
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<tr>
<td>Voltage at bus 6</td>
<td>1.100</td>
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</table>
When the wind speed is 9 m/s, the value of $P_g$ at bus 9 is changed to 1180 W, as shown in fig. 4.35.

Figure 4.35 Generators Data when the New Installed DG Delivers 50% Rated Power

The process of reactive power optimization, when DG produce 50% of its rated power output, is shown in fig. 4.36. Finally, the real power loss of the system converges on 12.1221 MW.
Figure 4.36 Loss Reduction Process when DG Delivers 50% Rated Power

Table 4.9 Optimization Results when DG Deliver 50% Rated Power

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<th>Values</th>
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<td>Shunt 9</td>
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</table>

When the wind speed is 10 m/s, the value of $P_g$ at bus 9 is changed to 1580 W, as shown in fig. 4.37.

Figure 4.37 Generators Data when the New Installed DG Delivers 75% Rated Power

The process of reactive power optimization, when DG produce 75% of its rated power output, is shown in fig. 4.38. Finally, the real power loss of the system is 12.0793 MW.
Figure 4.38 Loss Reduction Process when DG Delivers 75% Rated Power

Table 4.10 Optimization Results when DG Deliver 75% Rated Power

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<td>2</td>
<td>-4.571</td>
</tr>
<tr>
<td>7</td>
<td>-12.529</td>
</tr>
<tr>
<td>8</td>
<td>-12.529</td>
</tr>
<tr>
<td>13</td>
<td>-14.31</td>
</tr>
</tbody>
</table>

The phase angle shifts at the different real power output conditions are also compared in Table 4.11. When the output increases, the phase angle shift declines.

Table 4.11 Comparison of the Phase Angle Shift

<table>
<thead>
<tr>
<th>Turn ratio 2</th>
<th>0.9740</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn ratio 3</td>
<td>0.9971</td>
</tr>
<tr>
<td>Shunt 9</td>
<td>11.0650</td>
</tr>
</tbody>
</table>
4.5 Discussion

By analyzing the results of the three case studies, the following conclusions can be obtained:

1. Before the reactive power optimization, the reactive power in IEEE 14 bus system is unreasonable distributed. Reactive power dispatch can significantly reduce the real power loss of the system and improve the power quality.

2. Satisfying results can be achieved after about conducting 90 iterations, which reflects the excellent searching ability of PSO algorithm for solving nonlinear problems.

3. When a small capacity DG is added into the system, the real power loss would be further reduced. As the output of the DG increases, the real power loss of the system decreases.
Chapter Five: Conclusion and Future Work

5.1 Conclusion

Reactive power dispatch is a nonlinear optimization problem that contains both continuous and discrete control variables. PSO is a heuristic global optimization algorithm that possesses high efficiency and robustness. PSO is less sensitive to the complexity of the objective functions. Therefore, it shows enormous potential for solving reactive power dispatch problems.

This thesis uses the IEEE 14 bus system as the test system. Both PSO algorithm and MATPOWER 5.1 toolbox are applied to reduce the real power loss in the power networks. In order to avoid the control variables exceeding the limits, exterior penalty function method is also employed. The main contribution of this thesis is as follows:

1. Reactive power dispatch approach can significantly reduce the power loss in power systems, and this method is both cost-effective and can be easily employed in real life.

2. PSO algorithm shows excellent searching ability in solving nonlinear optimization problems. Applying PSO algorithm to address the reactive power dispatch problems is technically feasible and can achieve considerable economic benefits.
3 The mature MATPOWER 5.1 toolbox are introduced to calculate the power flow and manage the equality constraints in PSO based reactive power dispatch. The accuracy of the results and the robustness of the code get improved.

5.2 Future Work

This thesis solves the reactive power dispatch problem and determines the optimal placement of newly installed DG in an existing power system. However, there still appears to be some limitations and need to do further research.

1 PSO algorithm has excellent searching capability, but it is apt to plunge into local minimum solutions. Further research needs to think about how to avoid premature problems.

2 The running time of the code is five minutes on the laptop. Future work includes improving the efficiency of the MATLAB code.

3 The modified test system only considers one DG. If more DGs are added to the systems, the computation time would be dramatically increased. Further research needs to simplify the power system model to reduce the computation time.

4 Due to the computation time limitation, this thesis only calculates the reactive power dispatch problems when the wind generator operates at 7 m/s, 9 m/s, and 10 m/s. In the future research, the performance of the proposed method at other wind speed conditions would also be calculated.
References


Appendix A  MATLAB Code for Reactive Power Dispatch without New DGs

```matlab
%% Reactive Power Dispatch  Initialization

%% Iteration=200, Swarm size=50
clear
clec
iter=0;
iteration=200;
particlenumber=50;

% Inertia Weight
w_max=0.9;
w_min=0.4;
w_temp=w_max;
w_step=(w_max-w_min)/iteration;

% Maximum and minimum limit
vol_min=0.95;
vol_max=1.10;

% Load IEEE 14 bus data
[baseMVA, bus, gen, branch]=loadcase(case14);

% Initialization of Swarm & velocity
% Control variables: vg1 (1.06), vg2 (1.045), vg3 (1.01), vg6 (1.07), vg8(1.09)
% Control variables: tp1(4-7 0.978), tp2(4-9 0.969), tp3(5-6 0.932)
% Control variables: shunt9(19)

% Random 50*9 matrix
Swarm=[unifrnd(0.95,1.10,particlenumber,5), ...
unifrnd(0.975,1.025,particlenumber,3),unifrnd(0,20,particlenumber,1)];

% Initial velocity is set to 0
Velocity=zeros(particlenumber,9);

for i=1:particlenumber
    v1=Swarm(i,1);  % V1
    bus(1,8)=v1;    % Vm, 8 is voltage magnitude (p.u.)
    gen(1,6)=v1;   % Vg, 6 is voltage magnitude setpoint (p.u.)
    v2=Swarm(i,2); % V2
    bus(2,8)=v2;
    gen(2,6)=v2;
```

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v3=Swarm(i,3);       %v3
bus(3,8)=v3;
gen(3,6)=v3;
v6=Swarm(i,4);       %v6
bus(6,8)=v6;
gen(4,6)=v6;
v8=Swarm(i,5);       %v8
bus(8,8)=v8;
gen(5,6)=v8;

branch(8,9)=Swarm(i,6);    %tp1 4-7, 9 is tap position
branch(9,9)=Swarm(i,7);    %tp2 4-9
branch(10,9)=Swarm(i,8);  %tp3 5-6
bus(9,6)=Swarm(i,9);    %Shunt capacitor 9, 6 is BS

eval(['savecase (''case14_test' num2str(i) '.mat'', baseMVA, bus, gen, branch)']);
eval(['results',num2str(i),'=runpf(''case14_test', num2str(i) '.mat'')']);
eval(['losses',num2str(i),'=sum(real(get_losses(results',num2str(i),')))]);

%Penalty for bus voltage violation
bus_inf=bus(:,8);
for bus_num=1:14
    if bus_inf(bus_num)>vol_max
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_max)^2;
    elseif bus_inf(bus_num)<vol_min
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_min)^2;
    else
        penalty_bus(bus_num)=0;
    end
end
penalty_bus_violation=sum(penalty_bus);

%Penalty for reactive generation violation
gen_inf=gen(:,3);
for gen_num=2:5
    if gen_inf(gen_num)>gen(gen_num,4)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,4))^2;
    elseif gen_inf(gen_num)<gen(gen_num,5)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,5))^2;
    else
        penalty_gen(gen_num)=0;
    end
penalty_gen_violation=sum(penalty_gen);

%Penalty for tap position violation
brch_inf=[branch(8,9); branch(9,9); branch(10,9)];
for brch_num=1:3
  if brch_inf(brch_num)>1.025
    penalty_brch(brch_num)=10000*(brch_inf(brch_num)-1.025)^2;
  elseif brch_inf(brch_num)<0.975
    penalty_brch(brch_num)=10000*(brch_inf(brch_num)-0.975)^2;
  else
    penalty_brch(brch_num)=0;
  end
end
penalty_brch_violation=sum(penalty_brch);

%Penalty function
losses(i)=eval(['losses',num2str(i)]);
Obj_fun_initial(i)=losses(i)+penalty_bus_violation+penalty_gen_violation+penalty_brch_violation;
end

%%%%%%%%%%%%%%%% Initialize Pbest and Gbest %%%%%%%%%%%%%%%%%
for j=1:particlenumber
  Pbest(j,:)=Swarm(j,:);
  Val_Pbest(j)=Obj_fun_initial(j);
end
[Val_Gbest,m]=min(Val_Pbest);
Gbest=Swarm(m,:);
Gbest_calc=repmat(Swarm(m,:),particlenumber,1);

%%%%%%%%%%%%%%%% PSO %%%%%%%%%%%%%%%%%
losses_temp=zeros(1,particlenumber);
figure('NumberTitle', 'off', 'Name', 'Minimum Real Power Loss');
title('Minimum Real Power Loss');
ylabel('Real Power Loss (MW)');
xlabel('Iteration');
grid on;
hold on
for iter=1:iteration
R1=rand(particlenumber,9);
R2=rand(particlenumber,9);
%2.05+2.05=4.1;
%2/abs(2-4.1-sqrt(4.1*4.1-4*4.1))=0.729
Velocity=0.729*(w_temp*Velocity+2.05*R1.*(Pbest-Swarm)+2.05*R2.*(Gbest_calc-Swarm));

% Set maximum velocity
for v_iter=1:9
    if v_iter==9
        Outstep=Velocity(:,v_iter)>0.1;
        Velocity(find(Outstep),v_iter)=0.1;
        Outstep=Velocity(:,v_iter)<-0.1;
        Velocity(find(Outstep),v_iter)=-0.1;
    else
        Outstep=Velocity(:,v_iter)>0.003;
        Velocity(find(Outstep),v_iter)=0.003;
        Outstep=Velocity(:,v_iter)<-0.003;
        Velocity(find(Outstep),v_iter)=-0.003;
    end
end

Swarm=Swarm+Velocity;

for k=1:particlenumber
    v1=Swarm(k,1);  \%v1
    bus(1,8)=v1;   \%Vm, 8 is voltage magnitude (p.u.)
    gen(1,6)=v1; \%Vg, 6 is voltage magnitude setpoint (p.u.)
    v2=Swarm(k,2);  \%v2
    bus(2,8)=v2;
    gen(2,6)=v2;
    v3=Swarm(k,3); \%v3
    bus(3,8)=v3;
    gen(3,6)=v3;
    v6=Swarm(k,4);   \%v6
    bus(6,8)=v6;
    gen(4,6)=v6;
    v8=Swarm(k,5); \%v8
    bus(8,8)=v8;
    gen(5,6)=v8;

    branch(8,9)=Swarm(k,6);  \%tp1 4-7, 9 is tap position
    branch(9,9)=Swarm(k,7);  \%tp2 4-9
branch(10,9)=Swarm(k,8);  %tp3 5-6

bus(9,6)=Swarm(k,9);    %Shunt capacitor 10, 6 is BS

eval(['savecase ("case14_test' num2str(k) '.mat", baseMVA, bus, gen, branch)']);
eval(['results',num2str(k),'=runpf("case14_test', num2str(k) '.mat")']);
eval(['losses',num2str(k),'=sum(real(get_losses(results',num2str(k),')))']);

%Penalty for bus voltage violation
bus_inf=bus(:,8);
for bus_num=1:14
    if bus_inf(bus_num)>vol_max
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_max)^2;
    elseif bus_inf(bus_num)<vol_min
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_min)^2;
    else
        penalty_bus(bus_num)=0;
    end
end
penalty_busViolation=sum(penalty_bus);

%Penalty for reactive generation violation
gen_inf=gen(:,3);
for gen_num=2:5
    if gen_inf(gen_num)>gen(gen_num,4)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,4))^2;
    elseif gen_inf(gen_num)<gen(gen_num,5)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,5))^2;
    else
        penalty_gen(gen_num)=0;
    end
end
penalty_genViolation=sum(penalty_gen);

%Penalty for tap position violation
brch_inf=[branch(8,9); branch(9,9); branch(10,9)];
for brch_num=1:3
    if brch_inf(brch_num)>1.025
        penalty_brch(brch_num)=10000*(brch_inf(brch_num)-1.025)^2;
    elseif brch_inf(brch_num)<0.975
        penalty_brch(brch_num)=10000*(brch_inf(brch_num)-0.975)^2;
    else
        penalty_brch(brch_num)=0;
    end
end
penalty_brchViolation=sum(penalty_brch);
penalty_brch_violation = sum(penalty_brch);

% Penalty function
losses_temp(k) = eval(['losses', num2str(k)]);

Obj_fun_temp(k) = losses_temp(k) + penalty_bus_violation + penalty_gen_violation + penalty_brch_violation;

if Obj_fun_temp(k) < Val_Pbest(k)
    losses(k) = losses_temp(k);
    Val_Pbest(k) = Obj_fun_temp(k);
    Pbest(k,:) = Swarm(k,:);
end

[Val_Gbest_temp,n] = min(Val_Pbest);
if Val_Gbest_temp < Val_Gbest
    Val_Gbest = Val_Gbest_temp;
    Gbest = Swarm(n,:);
    Gbest_calc = repmat(Swarm(n,:), particlenumber, 1);
end
w_temp = w_temp - w_step;
Val_Gbest_rec(iter) = Val_Gbest;
plot(Val_Gbest_rec);
drawnow;
end
Appendix B  MATLAB Code for Reactive Power Dispatch with a New DG Installed on PQ Bus

%%% Reactive Power Dispatch %%
%%% System initialization %%
%Iteration=200, Swarm size=50

clear
clc
iter=0;
iteration=200;
particlenumber=50;

%Inertia Weight
w_max=0.9;
w_min=0.4;
w_temp=w_max;
w_step=(w_max-w_min)/iteration;

%Maximum and minimum limit
vol_min=0.95;
vol_max=1.10;

%Load Modified IEEE 14 bus data
[baseMVA, bus, gen, branch]=loadcase(case14_bus4);

%Initialization of Swarm & velocity
%Control variables: vg1 (1.06), vg2 (1.045), vg3 (1.01), vg6 (1.07)
%vg8(1.09) vg4(1.019)
%Control variables: tp1(4-7 0.978), tp2(4-9 0.969), tp3(5-6 0.932)
%Control variables: shunt9(19)

%Random 50*10 matrix
Swarm=[unifrnd(0.95,1.10,particlenumber,6), ... 
   unifrnd(0.975,1.025,particlenumber,3),unifrnd(0,15,particlenumber,1)];

%Initial velocity is set to 0
Velocity=zeros(particlenumber,10);

for i=1:particlenumber
   v1=Swarm(i,1);  %v1
   bus(1,8)=v1;    %Vm, 8 is voltage magnitude (p.u.)
   gen(1,6)=v1;   %Vg, 6 is voltage magnitude setpoint (p.u.)
   v2=Swarm(i,2); %v2
bus(2,8)=v2;  
gen(2,6)=v2;  
v3=Swarm(i,3);  
bus(3,8)=v3;  
gen(3,6)=v3;  
v6=Swarm(i,4);  
bus(6,8)=v6;  
gen(4,6)=v6;  
v8=Swarm(i,5);  
bus(8,8)=v8;  
gen(5,6)=v8;  
v4=Swarm(i,6);  
bus(4,8)=v4;  
gen(6,6)=v4;

branch(8,9)=Swarm(i,7);  \%tp1 4-7, 9 is tap ratio  
branch(9,9)=Swarm(i,8);  \%tp2 4-9 
branch(10,9)=Swarm(i,9);  \%tp3 5-6 

bus(9,6)=Swarm(i,10);  \%Shunt capacitor 9, 6 is BS

eval(['savecase (''case14_test' num2str(i) '.mat'', baseMVA, bus, gen, branch)']); 
eval(['results',num2str(i),']=runpf(''case14_test', num2str(i) '.mat''));
eval(['losses',num2str(i),']=sum(real(get_losses(results',num2str(i),'))));

% Penalty for bus voltage violation 
bus_inf=bus(:,8);  
for bus_num=1:14
    if bus_inf(bus_num)>vol_max
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_max)^2;
    elseif bus_inf(bus_num)<vol_min
        penalty_bus(bus_num)=10000*(bus_inf(bus_num)-vol_min)^2;
    else
        penalty_bus(bus_num)=0;
    end
end
penalty_bus_violation=sum(penalty_bus);

% Penalty for reactive generation violation 
gen_inf=gen(:,3);  
for gen_num=2:6
    if gen_inf(gen_num)>gen(gen_num,4)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,4))^2;
    elseif gen_inf(gen_num)<gen(gen_num,5)
        penalty_gen(gen_num)=1000*(gen_inf(gen_num)-gen(gen_num,5))^2;
    else
        penalty_gen(gen_num)=0;
    end
end
penalty_gen_violation=sum(penalty_gen);
else
    penalty_gen(gen_num)=0;
end
end

penalty_gen_violation=sum(penalty_gen);

% Penalty function
losses(i)=eval(['losses',num2str(i)]);
Obj_fun_initial(i)=losses(i)+penalty_bus_violation+penalty_gen_violation;
end

%%%%%% Initialize Pbest and Gbest %%%%%
for j=1:particlenumber
    Pbest(j,:)=Swarm(j,:);
    Val_Pbest(j)=Obj_fun_initial(j);
end

[Val_Gbest,m]=min(Val_Pbest);
Gbest=Swarm(m,:);
Gbest_calc=repmat(Swarm(m,:),particlenumber,1);

%%%%%% PSO loop %%%%%
losses_temp=zeros(1,particlenumber);
figure('NumberTitle', 'off', 'Name', 'Minimum Real Power Loss');
title('Minimum Real Power Loss');
ylabel('Real Power Loss (MW)');
xlabel('Iteration');
grid on;
hold on

for iter=1:iteration
    R1=rand(particlenumber,10);
    R2=rand(particlenumber,10);
    % 2.05+2.05=4.1;
    % 2/abs(2-4.1-sqrt(4.1*4.1-4*4.1))=0.729
    Velocity=0.729*(w_temp*Velocity+2.05*R1.*(Pbest-Swarm)+2.05*R2.*(Gbest_calc-Swarm));

    % Set maximum velocity
    for v_iter=1:10
        if v_iter==10
            Outstep=Velocity(:,v_iter)>0.1;
            Velocity(find(Outstep),v_iter)=0.1;
        end
    end

    for j=1:particlenumber
        Swarm(j,:)=Swarm(j,:)+Velocity(j,:);
        losses_temp(j)=eval(['losses',num2str(j)]);
        Obj_fun_initial(j)=losses_temp(j)+penalty_bus_violation+penalty_gen_violation;
    end
    % Calculate new gbest
    [Val_Gbest,m]=min(Val_Pbest);
    Gbest=Swarm(m,:);
    Gbest_calc=repmat(Swarm(m,:),particlenumber,1);
end
Outstep=Velocity(:,v_iter)<-0.1;
Velocity(find(Outstep),v_iter)=-0.1;
else
Outstep=Velocity(:,v_iter)>0.003;
Velocity(find(Outstep),v_iter)=0.003;
Outstep=Velocity(:,v_iter)<-0.003;
Velocity(find(Outstep),v_iter)=-0.003;
end
end
Swarm=Swarm+Velocity;

for k=1:particlenumber
v1=Swarm(k,1);       %v1
bus(1,8)=v1;         %Vm, 8 is voltage magnitude (p.u.)
gen(1,6)=v1;         %Vg, 6 is voltage magnitude setpoint (p.u.)
v2=Swarm(k,2);       %v2
bus(2,8)=v2;
gen(2,6)=v2;
v3=Swarm(k,3);       %v3
bus(3,8)=v3;
gen(3,6)=v3;
v6=Swarm(k,4);       %v6
bus(6,8)=v6;
gen(4,6)=v6;
v8=Swarm(k,5);       %v8
bus(8,8)=v8;
gen(5,6)=v8;
v4=Swarm(k,6);       %v4
bus(4,8)=v4;
gen(6,6)=v4;
branch(8,9)=Swarm(k,7);   %tp1 4-7, 9 is tap ratio
branch(9,9)=Swarm(k,8);   %tp2 4-9
branch(10,9)=Swarm(k,9);  %tp3 5-6
bus(9,6)=Swarm(k,10);   %Shunt capacitor 10, 6 is BS

eval(['savecase (''case14_test' num2str(k) '.mat'', baseMVA, bus, gen, branch)']);
eval(['results',num2str(k),'=runpf(''case14_test', num2str(k) '.mat'')]);
eval(['losses',num2str(k),'=sum(real(get_losses(results',num2str(k),')))']);

%Penalty for bus voltage violation
bus_inf = bus(:, 8);
for bus_num = 1:14
    if bus_inf(bus_num) > vol_max
        penalty_bus(bus_num) = 10000 * (bus_inf(bus_num) - vol_max)^2;
    elseif bus_inf(bus_num) < vol_min
        penalty_bus(bus_num) = 10000 * (bus_inf(bus_num) - vol_min)^2;
    else
        penalty_bus(bus_num) = 0;
    end
end
penalty_bus_violation = sum(penalty_bus);

% Penalty for reactive generation violation
gen_inf = gen(:, 3);
for gen_num = 2:6
    if gen_inf(gen_num) > gen(gen_num, 4)
        penalty_gen(gen_num) = 1000 * (gen_inf(gen_num) - gen(gen_num, 4))^2;
    elseif gen_inf(gen_num) < gen(gen_num, 5)
        penalty_gen(gen_num) = 1000 * (gen_inf(gen_num) - gen(gen_num, 5))^2;
    else
        penalty_gen(gen_num) = 0;
    end
end
penalty_gen_violation = sum(penalty_gen);

% Penalty function
losses_temp(k) = eval(['losses', num2str(k)]);
Obj_fun_temp(k) = losses_temp(k) + penalty_bus_violation + penalty_gen_violation;

if Obj_fun_temp(k) < Val_Pbest(k)
    losses(k) = losses_temp(k);
    Val_Pbest(k) = Obj_fun_temp(k);
    Pbest(k, :) = Swarm(k, :);
end
end

[Val_Gbest_temp, n] = min(Val_Pbest);
if Val_Gbest_temp < Val_Gbest
    Val_Gbest = Val_Gbest_temp;
    Gbest = Swarm(n, :);
    Gbest_calc = repmat(Swarm(n, :) , particlenumber, 1);
end
w_temp = w_temp - w_step;
Val_Gbest_rec(iter)=Val_Gbest;
plot(Val_Gbest_rec);
drawnow;
end