

## Optimal Regulation for Loop-closing Operation in a Distributed Generation Integrated System

As an effective measure to improve electricity supply reliability, loop-closing operation is widely used in distribution network. Due to various distributed generation were involved into distributed system, problems such as circuit breaker overcurrent may arise if loop-closing and DG status were not well coordinated. In this paper, a new loop-closing control model which including distributed generation is proposed, and the genetic algorithm with diversity control approach is used to solve the problem. A typical case with two feeders and three distributed generations is used to illustrate the performance of the proposed method.

Keywords: loop-closing operation; distribution system; distributed generation; genetic algorithm; diversity control.

### 1. Introduction

Most distribution systems were designed to be in meshed form and are operated in radial form in China<sup>[1]</sup>; therefore, load can be shifted from one source to another by toggling the status of corresponding tie-switch when necessary. Figure 1 shows a typical network in which substation 1, 2 and 3 are separated by three tie-switches (A4, A5, and A6). When the load of a substation (e.g. substation 3) is heavy and another substation (e.g. substation 1) is relatively light, load can be transferred by exchanging the state of two or more sectionalizers (e.g. A3 and A5). In order to avoid supply outage, the normally-open tie-switch (e.g. A5) is allowed to be closed before the action of the switch which to be opened (e.g. A3), and the system will be temporarily in a so called loop-closing status. However, improper loop-closing action may bring some negative effects such as over-current or mal-operation of the circuit breaker at the feeder root (e.g. S1)<sup>[2]</sup>. It is necessary to calculate and regulate the current which flowing through the tie-switch during loop-closing operation.

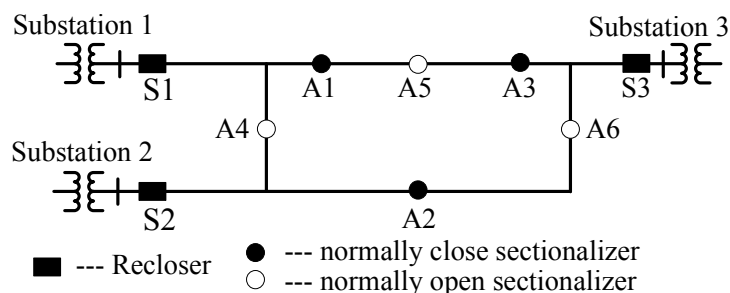


Figure 1 Typical distribution network with 3 feeders

Some effort has been spent on analyzing the loop-closing current. The superposition principle is applied in [3] to get the steady power flow after loop-closing operation. A frequency domain model which using the Laplace transform technique is proposed in [4] for calculating the instantaneous loop-closing impact current. Authors in [5] used the

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PSCAD/EMTDC software to establish the loop-closing model and obtained the upper and lower limit of steady state current. A loop-closing analyze tool is developed by authors in [6], in which several loop templates are predefined and the corresponding loop currents are calculated off-line.

Obviously, if the system status is properly adjusted by regulating some electrical devices before operating tie switches, so that the current produced during loop-closing is reduced, it will effectively improve the success rate of loop-closing operation. The devices that can be used to control the system state may include transformer taps, capacitors, reactors, etc. However, corresponding research in this area is still very limited at present. The factors that impact the loop-closing current is analyzed in [7], and regulation strategies are proposed based on the sensitivities of loop current to those factors. An optimal power flow control method is proposed in [1] which utilized the Unified Power Flow Controller (UPFC) to control the status of the distribution network.

As an efficient, economical and environmentally friendly alternative to traditionally fuel-fired sources, distributed generation (DG) has been gradually extended in many countries in the distribution system. As a result, the electricity distribution system has changed from single power supply system to multi-power supply system when DG merged into the grid, and this will have profound and complex effects in several aspects including loop-closing operation. The impact of distributed generation on loop-closing current is simulated in [8]. The schedulable DG units may play an active role in controlling loop-closing current in active distribution network (ADN). Therefore, optimized schedule of DGs and other electrical devices are necessary to ensure the safety of loop-closing operation.

This paper is organized as follows. In section 3, the optimal loop-closing regulation model is proposed. In section 4, a genetic algorithm with diversity control is introduced to solve the optimal loop-closing problem. In section 5, a typical distribution network is used to illustrate the effectiveness of our approach. Finally, our work of this paper is summarized in the last section.

## 2. Notation

<b>N</b>	set of total buses
<b>L</b>	set of total branches
<b>G<sup>S</sup></b>	set of schedulable distributed generations
<b>T<sup>OLTC</sup></b>	set of transformers with on-load tap changer
<b>G<sub>p</sub></b>	set of DGs of which the active power is schedulable
<b>G<sub>o</sub></b>	set of DGs of which the reactive power is schedulable
<b>G<sub>v</sub></b>	set of DGs of which the terminal voltage is controllable
<b>G<sub>I</sub></b>	set of DGs of which the injection current is controllable
$S_{g,i}$	apparent power generation of distributed generator $i$
$V_{g,i}$	voltage magnitude at the bus of distributed generator $i$
$I_{g,i}$	injection current of distributed generator $i$
$\tau_j$	position of tap changer $j$
$\tau_j^{\max}$	top position of tap changer $j$
$\tau_j^{\min}$	bottom position of tap changer $j$
$I_{lc,k}$	current of branch $k$ which to be closed

$P_{Si}$	injection active power at bus $i$
$Q_{Si}$	injection reactive power at bus $i$
$P_{D,i}$	active power demand at bus $i$
$Q_{D,i}$	reactive power demand at bus $i$
$I_{D0,i}$	extraction current of load at bus $i$
$Q_{C,i}$	reactive power compensated by shunt devices at bus $i$
$G_{ij}$	real part of the $ij^{th}$ element of the $Y$ -bus matrix
$B_{ij}$	imaginary part of the $ij^{th}$ element of the $Y$ -bus matrix
$V_i, V_j$	voltage magnitude at bus $i$ and bus $j$
$\theta_{ij}$	voltage angle difference between bus $i$ and bus $j$
$I_{b,i}$	current of branch $i$
$I_{b,i}^{max}$	maximum current limit of branch $i$
$P_{g,i}$	active power generation of DG $i$
$Q_{g,i}$	reactive power generation of DG $i$
$P_{gi}^{max}$	active power upper limit of DG $i$
$P_{gi}^{min}$	active power lower limit of DG $i$
$Q_{gi}^{max}$	reactive power upper limit of DG $i$
$Q_{gi}^{min}$	reactive power lower limit of DG $i$
$V_{g,i}$	terminal voltage of DG $i$
$V_{gi}^{max}$	voltage magnitude upper limit of DG $i$
$V_{gi}^{min}$	voltage magnitude lower limit of DG $i$
$I_{g,i}$	injection current of DG $i$
$I_{gi}^{max}, I_{gi}^{min}$	upper and lower limit of $I_{g,i}$

### 3. Problem formulation

This section presents the mathematical formulation of the loop-closing regulation problem with distributed generation considered. The implemented backward and forward sweep load flow method is also presented in this section.

#### 3.1. Assumptions

To simplify the analysis, the following assumptions are employed in problem formulation:

- 1) The unbalance feature of distribution systems is not considered in the current optimization model.
- 2) For convenience, here DGs are classified into schedulable DGs and un-schedulable DGs.
- 3) Loads are represented by constant power model.

#### 3.2. Objective function

In order to improve the success rate of loop-closing operation, the loop-closing current  $I_{lc,k}$  should be minimized:

$$\min I_{lc,k} (S_{g,i}, \dot{V}_{g,i}, \dot{I}_{g,i}, \tau_j) \quad i \in \mathbf{G}^S, j \in \mathbf{T}^{OLTC} \quad (1)$$

$I_{lc,k}$  is a function of several variables, including schedulable DGs' power  $S_{g,i}$ , voltage  $V_{g,i}$ , injection current  $I_{g,i}$ , and transformers' tap position  $\tau_j$ .

### 3.3. Constraints

The final loop-closing regulation scheme should satisfy the following conditions:

1) Power balance constraint. The active and reactive power should be balanced at each bus:

$$P_{Si} - P_{D,i} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0, \quad i \in \mathbf{N} \quad (2)$$

$$Q_{Si} - Q_{D,i} + Q_{C,i} - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0, \quad i \in \mathbf{N} \quad (3)$$

2) Branch thermal limit. The magnitude of current  $I_{b,i}$  of each branch  $i$  should be kept below the thermal limit  $I_{b,i}^{\max}$  to maintain security of feeder lines:

$$|I_{b,i}| \leq I_{b,i}^{\max}, \quad i \in \mathbf{L} \quad (4)$$

3) DG power limit. For DGs which apply PQ strategy, the active power  $P_{g,i}$  and reactive power  $Q_{g,i}$  should not exceed the corresponding limits.

$$P_{gi}^{\min} \leq P_{g,i} \leq P_{gi}^{\max}, \quad i \in \mathbf{G}^S \quad (5)$$

$$Q_{gi}^{\min} \leq Q_{g,i} \leq Q_{gi}^{\max}, \quad i \in \mathbf{G}^S \quad (6)$$

4) DG voltage limit. For DGs which apply V/f strategy, the terminal voltage magnitude  $V_{g,i}$  should not exceed the corresponding limits.

$$V_{gi}^{\min} \leq V_{g,i} \leq V_{gi}^{\max}, \quad i \in \mathbf{G}^S \quad (7)$$

5) DG injection current limit. For DGs which apply constant current strategy, the magnitude of injection current  $I_{g,i}$  should always keep in the specified scope.

$$I_{gi}^{\min} \leq I_{g,i} \leq I_{gi}^{\max}, \quad i \in \mathbf{G}^S \quad (8)$$

6) Tap position limit. The location of each tap changer  $\tau_j$  must satisfy:

$$\tau_j^{\min} \leq \tau_j \leq \tau_j^{\max}, \quad j \in \mathbf{T}^{OLTC} \quad (9)$$

Equation (1) ~ equation (9) forms the optimal loop-closing regulation (OLCR) model. The decision variables include  $S_{g,i}$ ,  $V_{g,i}$ ,  $I_{g,i}$  and  $\tau_j$ .

### 3.4. Load flow

To get the magnitude of the current flowing through the closed tie switch, load flow calculation should be conducted when the values of decision variables are given.

A variety of power flow algorithms have been proposed in existing literatures<sup>[9-13]</sup>, for simplicity and efficiency, here the backward and forward sweep method is applied<sup>[14-15]</sup>. Figure 2 shows a typical feeder branch with DGs connected at the terminals.

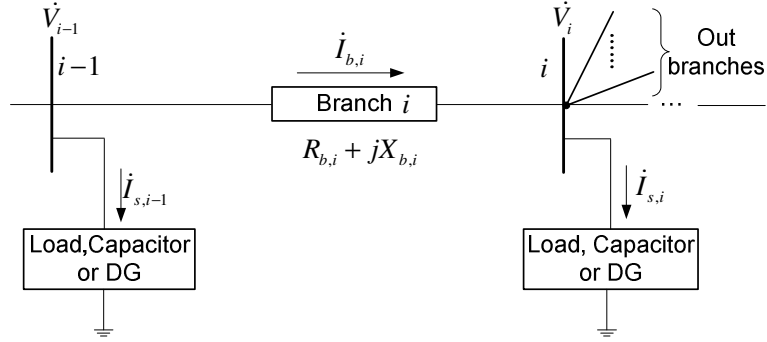


Figure 2 Backward and forward sweep power flow calculation

1) Backward sweep. The backward sweep proceeds from the end branch of feeder to the source. All branch currents are updated according to the bus voltages calculated in the forward sweep step. For bus  $i$  in Figure 2, suppose the extraction current of load is  $\dot{I}_{D,i}$ , the injection currents of capacitor and DG are  $\dot{I}_{C,i}$  and  $\dot{I}_{G,i}$  respectively, then the branch current  $\dot{I}_{b,i}$  can be expressed as following:

$$\dot{I}_{b,i} = \dot{I}_{D,i} - \dot{I}_{C,i} - \dot{I}_{G,i} + \sum \dot{I}_k \quad (10)$$

2) Forward sweep. The forward sweep starts from the source bus and proceeds in the downstream direction. All bus voltages are updated according to the branch currents calculated in the backward sweep step. For bus  $i$  in Figure 2, the voltage  $\dot{V}_i$  is determined by:

$$\dot{V}_i = \dot{V}_{i-1} - \dot{I}_{b,i}(R_{b,i} + jX_{b,i}) \quad (11)$$

3) Convergence criterion. The load flow algorithm will stop if the following condition is satisfied or the maximum number of iteration is reached:

$$\max \{ |\dot{V}_i(k) - \dot{V}_i(k-1)| \} < \varepsilon, i \in \mathbf{N} \quad (12)$$

### 3.5. Loop-closing current

When the tie switch is closed, the radial structure will change into a weak-loop network structure. The traditional sweep power flow doesn't work well in dealing with mesh structure. Here the superposition principle of linear circuit is applied to get the value of loop current as shown in Figure 3.

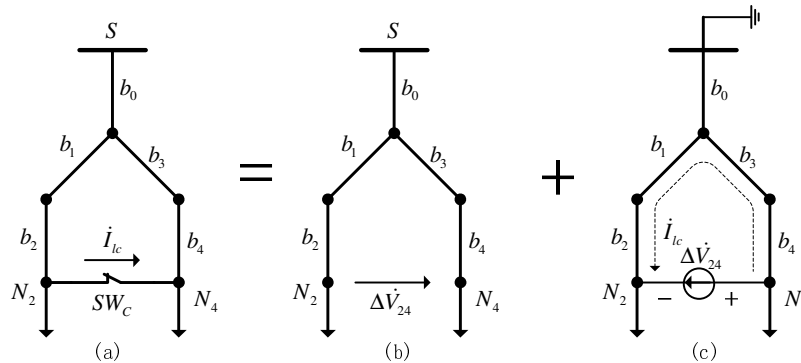


Figure 3 Resolution of loop current

The response in any branch of the feeder with a loop (Fig.3 (a)) is the sum of the response caused by the source  $S$  in the feeder without loop (Fig.3 (b)) and the response caused by the equivalent voltage source  $\Delta\dot{V}_c$  ( $\Delta\dot{V}_{24}$  in Fig.3 (c)). The voltage  $\Delta\dot{V}_c$  can be easily obtained by the backward and forward sweep load flow algorithm described in section 3.4. As a result, the loop-closing current  $\dot{I}_{lc}$  can be written as:

$$\dot{I}_{lc} = \Delta\dot{V}_c / \sum Z_{loop} \tag{13}$$

where  $Z_{loop}$  is the sum of impedance of all components in the loop. For the circuit in Figure 3,  $Z_{loop} = Z_{b1} + Z_{b2} + Z_{b3} + Z_{b4}$ .

#### 4. Solution algorithm

##### 4.1. Genetic algorithm with diversity control

Since  $S_{g,i}$ ,  $V_{g,i}$ , and  $I_{g,i}$  are continuous variables, while transformer tap position  $\tau_j$  has a discrete nature, the OLCR model formulated in Section 3.2 and Section 3.3 is a mixed-discrete nonlinear programming problem (MDNLP) which is difficult to get analytic solution. In recent decades, evolutionary computation techniques [16-20] such as genetic algorithm (GA) got rapid development because of their adaptive and global search ability. GA is easy to understand and easy to implement, and it has been successfully applied to power system optimization problems including economic dispatch, reactive power optimization, and power system planning. However, a major disadvantage of GA is that it is easy to trap into local optimum due to premature convergence.

Various mechanisms have been proposed in the literature to avoid the premature convergence, and one efficient measure is to take diversity control during GA operation. Researchers announced that early convergence could be effectively overcome if keeping proper diversity in the evolutionary process.

The genetic algorithm with diversity control<sup>[21]</sup> (GADC) is adopted to solve the OLCR problem. The flowchart of GADC is shown in Figure 4.

The diversity of population is measured by the Hamming distance between different chromosomes which is defined as:

$$H(x, y) = \sum_i |\text{sgn}(x[i] - y[i])| \tag{14}$$

where  $x[i]$  and  $y[i]$  are the  $i$ -th gene of individual  $x$  and  $y$  respectively. And  $\text{sgn}(\square)$  is a sign function which is defined as follows:

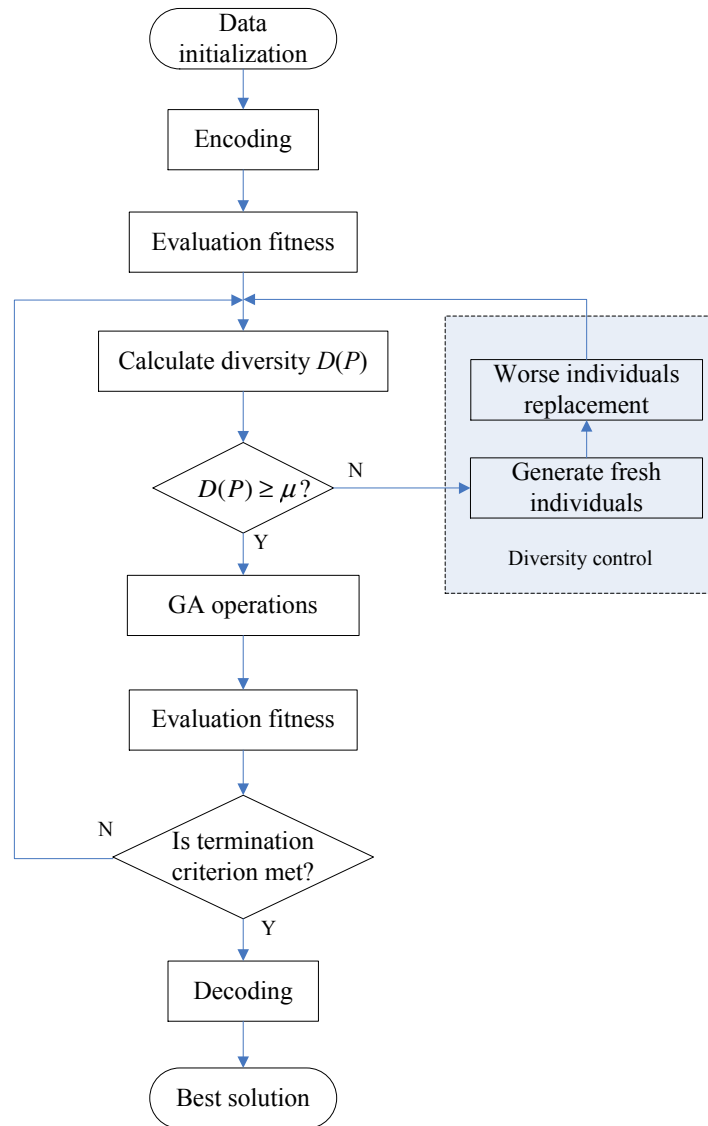


Figure 4 Flowchart of GADC

$$\text{sgn}(z) = \begin{cases} 1 & , z > 0 \\ 0 & , z = 0 \\ -1 & , z < 0 \end{cases} \quad (15)$$

Then the diversity of population  $P$  can be expressed as:

$$D(P) = \frac{1}{2} \sum_{i \neq j} H(P[i], P[j]) \quad (16)$$

where  $P[i]$  and  $P[j]$  are the  $i$ -th and  $j$ -th individual of population  $P$  respectively.

The value of each generation's diversity  $D(P)$  is monitored during the evolution to ensure the diversity is high enough, that is:

$$D(P) \geq \mu \quad (17)$$

where  $\mu$  is the preset diversity threshold.

If the above condition (equation (17)) is not satisfied, then a certain percentage of new chromosomes called fresh individuals are randomly generated, and the same amounts of

chromosomes with lowest fitness are kicked out from the population. This substitution process continues until the diversity threshold  $\mu$  is met.

#### 4.2. Dealing with constraints

Penalty function method is the most commonly used method of dealing with the constraint conditions. However, penalty factors are difficult to choose, and penalty factors also increase the dimension of solution space. Some literatures adopt optimal penalty factor or adaptive penalty factor, thus greatly increase the complexity for solving problem.

Here we adopt a pair-wise comparison method<sup>[22]</sup> which applying the following rules in the GA reproduction operation: 1) For two feasible solution, we choose the solution with higher fitness; 2) For the case of one feasible solution and one infeasible solution, we choose the feasible solution; 3) In the case of two infeasible solution, we chose the one with minimal constraint violation.

The fitness of a feasible solution is its objective function value, and the fitness of an infeasible solution is the objective function value of the worst feasible individual plus the constraint violation values.

The result of GADC gives the optimal configuration which including each DG's state and each transformer's tap position.

### 5. Case study

#### 5.1. Test system

A distribution system with two feeders and three DGs is developed to illustrate the effectiveness of the proposed loop-closing regulation approach. Figure 5 shows the structure of the system.

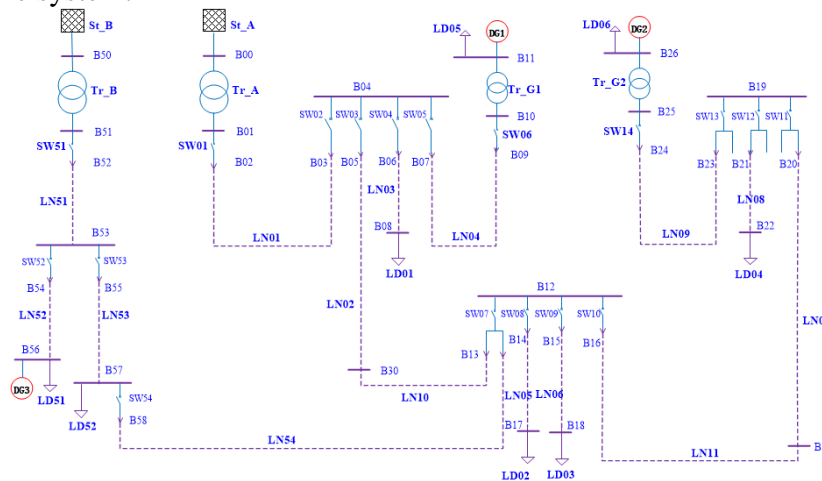


Figure 5 Test system

The parameters of lines, loads, and distributed generators are given in Table 1 and Table 2. The base power and base voltage are set to be 1000 kVA and 10.5kV respectively.



Table 1: Line parameters

Line ID	Impedance (p.u.)	Shunt susceptance (p.u.)
LN01	0.00816+j0.01088	0.00346
LN02	0.00363+j0.00726	0.00277
LN03	0.00091+j0.00363	0.00208
LN04	0.00181+j0.00726	0.00381
LN05	0.00363+j0.00363	0.00346
LN06	0.00317+j0.00363	0.00416
LN07	0.01134+j0.01814	0.00242
LN08	0.00091+j0.00363	0.00277
LN09	0.00363+j0.00726	0.00346
LN10	0.00399+j0.00726	0.00416
LN11	0.00209+j0.00363	0.00312
LN51	0.00290+j0.00726	0.00294
LN52	0.00490+j0.01088	0.00225
LN53	0.00435+j0.00726	0.00277
LN54	0.00490+j0.00726	0.00381

For simplicity, here we assume all the DGs are schedulable, and only output real power. The upper-limit and lower-limit of DG power are set to 100 percent and 30 percent of their rated power separately.

Table 2: Parameters of loads and distributed generations

Element type	Element name	Terminal bus	Rated voltage (kV)	Rated power (kW,kVar)
Loads	LD01	B08	10.5	100+j30
	LD02	B17	10.5	150+j50
	LD03	B18	10.5	120+j80
	LD04	B22	10.5	160+j90
	LD05	B11	0.4	120+j20
	LD06	B26	0.4	60+j15
	LD51	B56	10.5	200+j55
	LD52	B57	10.5	160+j35
Distributed generators	DG1	B11	0.4	200+j0
	DG2	B26	0.4	100+j0
	DG3	B56	10.5	100+j0

## 5.2. Influence factors of loop-current

There is a tie switch SW54 which is normally open in the above system. Loop current  $\dot{I}_{lc,54}$  will appear in branch LN54 after SW54 is closed.

To investigate the influence factors of loop current, we change the output active power of each DG and the tap position of transformer Tr\_A and Tr\_B, and record the value of  $\dot{I}_{lc,54}$  on each time SW54 closing. The test results are shown in Fig. 6.

As can be seen, the amplitude of loop-closing current  $\dot{I}_{lc,54}$  is closely related to DG power and transformer ratio. Due to the infeed current contributed by the upstream generator DG3,  $\dot{I}_{lc,54}$  increases with the increase of active power of DG3. On the other hand,

$\dot{I}_{lc,54}$  decreases with the increase of active power of the downstream generators DG1 and DG2 because of their outfeed effect.

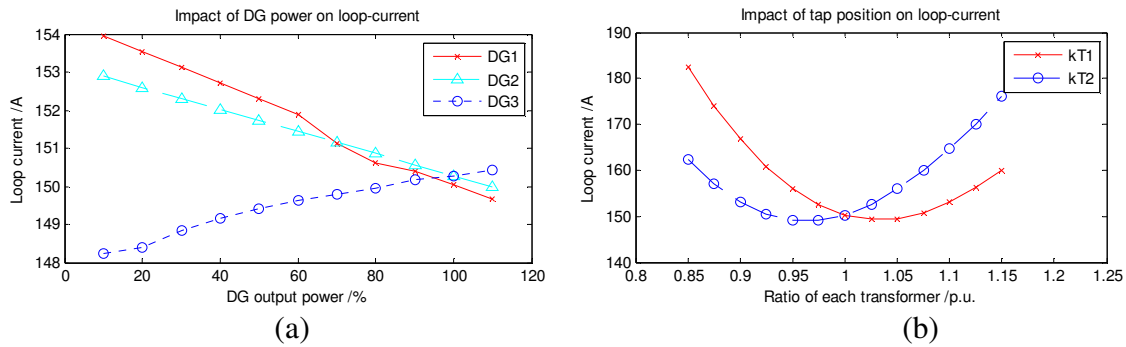


Figure 6 Impact of DG and transformer on loop current

In Fig.6 (b), kT1 and kT2 are the ratios of transformer Tr\_A and Tr\_B respectively. Since the loop-closing current is proportional to the voltage difference across the tie switch,  $\dot{I}_{lc,54}$  changes when adjusting the ratios kT1 and kT2. In the process of the change of the ratios from small to large, the direction of the reactive power flowing through switch SW54 will flip which cause loop current  $\dot{I}_{lc,54}$  reversing. As a result, there is an optimal configuration of transformer ratios which makes the loop-closing current minimum.

### 5.3. Loop-closing control schedule

Based on the proposed GADC algorithm, the loop-closing control model introduced in section 3 is solved. The maximum evolution iteration number is set to 200, and the threshold of population diversity  $\mu$  is 0.18. To illustrate the effect of diversity control, the classical Simple Genetic Algorithm (SGA) is also applied to solve the same loop-closing control problem. Figure 7 shows the diversity comparison results between GADC and SGA. The diversity will rebound when the value of  $D(P)$  reaches to the preset threshold 0.18 due to injection of fresh random individuals in GADC. However, in SGA, the diversity has been lower than  $1 \times 10^{-3}$  since generation 42 which may lead to premature.

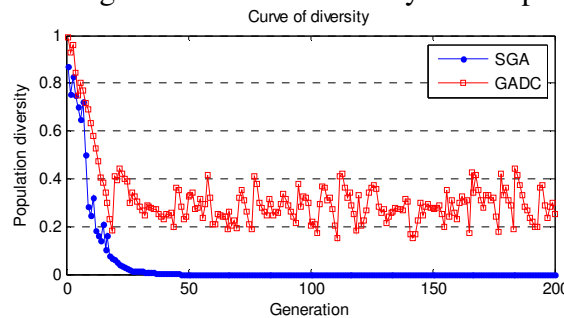


Figure 7 The population diversity of each generation

Figure 8 demonstrates the iteration process for SGA and GADC. We can discover that the SGA is prematurely falling into local optima before iteration 50. On the other hand, the fitness value of GADC continued to decline until 118<sup>th</sup> generation, which the fitness should be better than SGA as we expect.

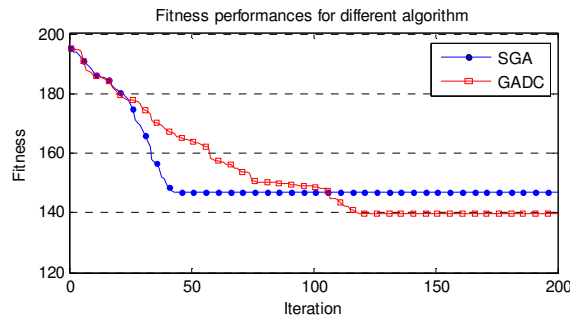


Figure 8 The fitness value of each generation

The final control schedule is listed in Table 3. The optimal result given by GADC is (0.996, 0.952, 0.325, 1.025, 0.975), which means the output power of DG1, DG2, and DG3 are 0.996, 0.952, and 0.325 times of their rated power, and the ratio of transformer TR\_A and TR\_B are 1.025 and 0.975 respectively. The loop-closing current of GADC reduced 4.86% than that of SGA, so the control schedule given by GADC is more secure.

Table 3: Loop-closing control schedule

Algorithm	Schedule	Fitness	Improvement
SGA	(0.981,0.937,0.382,1.05,0.925)	146.8	-
GADC	(0.996,0.952,0.325,1.025,0.975)	139.67	4.86%

## 6. Conclusion

An optimal loop-closing regulation model is proposed in this paper which takes distributed generation and OLTC transformer into account. Numerical results show that the output power of distributed generations and ratio of transformers may significantly influence the amplitude of loop-closing current.

To avoid the premature phenomenon of conventional genetic algorithm, we proposed a GADC optimization method which can keep the population diversity above a certain level. Comparing with the conventional simple genetic algorithm, our approach with diversity control is effective which can avoid falling into local optimum prematurely.

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