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Modified EP/sin for Optimal Power Flow with Economic Dispatch

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ABSTRACT

In this paper, evolutionary programming is modified to improve optimal power flow and economic dispatch problem. The first improvement is to enhance the power transfer capability of power transactions between generators and load buses. The second improvement is to determine the ratio of max power transfer capability per economic dispatch. Both improvements are evaluated under optimal power flow concepts and optimal allocation of the unified power flow controller. Particular optimal allocation of unified power flow controller includes optimal location and parameter settings. This optimal allocation is determined by this modified evolutionary programming. The main of modifying is to place the value of sine function in the mutation method. The IEEE 30-bus test system is used as a test system. Test results show that the proposed method gives the optimal allocation of unified power flow controller which makes the better overall results of optimal power flow with economic dispatch than original evolutionary programming.

Keyword: Evolutionary programming, Optimal power flow, Economic dispatch, Optimization

1. Introduction

According to the increasing demand for electrical power, this demand increases every year. There are many choices to supply this demand. The standard choice is to build a new power plant. The other choice is the addition of a sub power plant or distributed generation into the power system. However, the interesting alternate choice is to improve the power transfer capability of the electrical system by using the FACT controller. The FACTS controllers are the well-known electronics based devices which have been improved that their installation can be enhanced the power transfer capability [1]-[5].

However, the optimal allocation of the FACTS controller must be considered [6]-[12]. The maximum benefits from the installation of FACTS controllers are to optimize for their optimal allocation. This optimal allocation means the optimal location and parameter setting of each FACTS controller [13]. In this paper, the unified power flow controller (UPFC) which is the one type of FACTS controller is used.

Moreover, after the UPFC is installed and the power transfer capability is enhanced [14]. The economic dispatch (ED) should be considered. The ED contains the operating cost of the electrical power system [15]-[16]. The aim of ED solving is to reduce the fuel cost of all generators in the system to a minimum. In addition, the lowest fuel operating cost of the generator must provide enough electrical power to supply the load demand of the power system.

According to the above contents, the necessary thing is to find the optimal allocation of UPFC to response to these two improvements. In this paper, evolutionary programming (EP) is used to determine the allocation of UPFC. EP is one of the well-known heuristic method which has been proved that it can determine the optimal value for any complex optimization problem. However, the EP has chances to stick in the local area which gives the local answer. This is the disadvantage of EP.

In this paper, the EP is modified. The sine function is applied to EP. The specifics of using is to apply the value of sine function into the mutation method. The aim of this modifying is to take the EP step over from the local area. The IEEE 30-bus is used as a test system. The two objective problems are enhanced total transfer capability (TTC) and total transfer capability per ED, respectively. Both objective functions are operated with optimal power flow (OPF) concept [17]-[26]. Test results from EP with sine function are compared with the original EP.

2. Problem formulation

2.1. Total transfer capability (TTC)

TTC is defined as the capability of power transferring in the electrical power system. The electrical power, both real and reactive power will flow from the generators buses to load buses. According to the concept of optimal power flow (OPF), the equality and inequality constraints of the generator, voltage, power flow are used [22]. In addition, the operation limit of UPFC is set and set as a static model [27]. The equation of TTC determining is represented by (1)[28]-[29].

$$\max F_1 = TTC = \sum_{i=1}^{ND} P_{Di} + \sum_{i=1}^{NL} P_{Li} \quad (1)$$

Subject to

$$P_{Gi} - P_{Di} + \sum_{k=1}^{n(i)} P_{Ui}(V_{Ui}, \alpha_{Ui}) - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (2)$$

$$Q_{Gi} - Q_{Di} + \sum_{k=1}^{n(i)} Q_{Ui}(V_{Ui}, \alpha_{Ui}) + \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (3)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad \forall i \in NG \quad (4)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad \forall i \in NG \quad (5)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad \forall i \in N \quad (6)$$

$$V_j^{\min} \le V_j \le V_j^{\max} \qquad \forall j \in N \quad (7)$$

$$V_{Ui}^{\min} \le V_{Ui} \le V_{Ui}^{\max} \quad (8)$$

$$\alpha_{Ui}^{\min} \le \alpha_{Ui} \le \alpha_{Ui}^{\max} \quad (9)$$

Where

P_{Gi}	real power generation at the *i*th bus,
P_{Di}	real power loads in the *i*th bus,
P_{Li}	real power losses in the *i*th bus,
$P_{Ui}(V_{Ui}, \alpha_{Ui})$	injected real power of UPFC at bus i,
V_i	voltage magnitude at the *i*th bus,
V_j	voltage magnitude at the *j*th bus,
Y_{ij}	the magnitude of the element in *ij*th bus admittance matrix,
θ_{ij}	the angle of the element in *ij*th bus admittance matrix,
δ_i	voltage angles of the *i*th bus,
δ_j	voltage angles of the *j*th bus,
Q_{Gi}	reactive power generation at the

	*i*th bus,
Q_{Di}	reactive power load at the *i*th bus,
$Q_{Ui}(V_{Ui},\alpha_{Ui})$	injected reactive power of UPFC at bus i,
$P_{Gi}^{\min}$, $P_{Gi}^{\max}$	the lower and upper limit of real the power generation at the *i*th bus,
$Q_{Gi}^{\min}$, $Q_{Gi}^{\max}$	the lower and upper limit of reactive power generation at the *i*th bus,
$V_i^{\min}$, $V_i^{\max}$	lower and upper limit of voltage magnitude at the *i*th bus,
$V_j^{\min}$, $V_j^{\max}$	lower and upper limit of voltage magnitude at the jth bus,
$V_{Ui}^{\min}$, $V_{Ui}^{\max}$	minimum and maximum voltage limits of UPFC at line i,
$\alpha_{Ui}^{\min}$, $\alpha_{Ui}^{\max}$	minimum and maximum angle limits of UPFC at line i,
ND	number of load buses,
NL	number of lines,
N	total number of buses,

This objective function is used in case1 of this paper.

2.2. Economic dispatch (ED)

The ED contains about the operating cost of electrical power system. The objective function of the ED is express in (10) [30]-[32].

$$ED = \sum_{i=1}^{m} F_i\left(P_i\right) = \sum_{i=1}^{m}\left(a_i P_i^2 + b_i P_i + c_i\right) \qquad (10)$$

Where

ED	the total operating cost of the generator,
F_i	the cost function of the *i*th generator,
P_i	the electrical power of the *i*th generator,
m	the number of generators in the electrical power system, and
$a_i, b_i \, and \, c_i$	the cost coefficients of the *i*th generator.

2.3 TTC per ED

According to the real application, the performance of the electrical power system should not consider only the maximization of TTC or the minimization of fuel cost. The maximum TTC has the chance to give high or highest fuel costs which makes unprofitable. The minimum fuel cost has the chance to give too low TTC which cannot respond to the minimum requirement of TTC. Therefore, the minimum of ED should be indicated with maximum TTC in parallel. In this paper, the ratio of TTC and ED is set as another objective function in (11). The aim of this proposed is to maximize the objective function.

$$\max \quad F_2 = \frac{F_1}{ED} \qquad (11)$$

The unit of TTC is MW. The unit of ED, fuel cost is $/h. Thus, the unit of the objective function is MWh/$. The meaning is generated possible highest TTC in one hour per 1$. This objective function names TTC/ED and can be called benefit ratio. This objective function is used as case2 in this paper.

3. Proposed method

3.1. Evolutionary programming

Evolutionary programming (EP) is developed by L. J. Fogel in 1960 in order to use simulated evolution as a learning process aiming to generate artificial intelligence [33]-[39]. EP is well-known. Many papers contain the using of EP for optimization problem in power system [40]-[45]. Moreover, EP is used as a global optimization algorithm [46]. The main concept of EP is inspired by the theory of evolution by means of natural selection. The process of EP starts with initializing individuals in the population. After the objective function is evaluated. The selection process is started to select the individual as parents for the mutation to generate the next generation which is called offspring. The flowchart of EP is shown in Fig. 1.

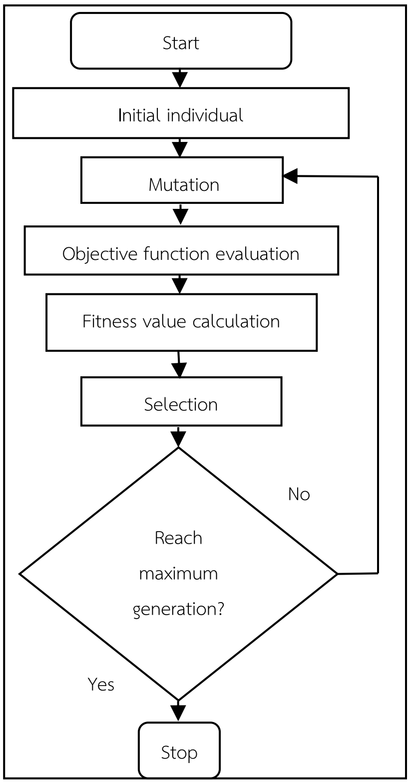

Fig 1. Flow chart of EP

The main components of the algorithm are briefly explained as follows.

The initial individual is initialized randomly using sets of uniform random number distribution ranging over the limitation of each control variable as (12).

$$x_i = x_i^{\min} + u\left(x_i^{\max} - x_i^{\min}\right) \quad (12)$$

Where

x_i value of the *i*th individual,

$x_i^{\min}, x_i^{\max}$ minimum and maximum value of the *i*th individual, and

u define between [0,1].

The Gaussian mutation operator is used in the mutation method. A new offspring is computed by using as (13) and (14).

$$x'_{k,i} = x_{k,i} + N\left(0, \sigma_{k,i}^2\right) \quad (13)$$

$$\sigma_{k,i} = \left(x_i^{\max} - x_i^{\min}\right)\left(\frac{f_{\max} - f_k}{f_{\max}} + a^g\right) \quad (14)$$

Where

$x'_{k,i}$ value of the *i*th individual of the *k*th offspring individual,

$x_{k,i}$ value of the *i*th individual of *k*th parent individual,

$N\left(0, \sigma_{k,i}^2\right)$ Gaussian random number with a mean of zero and standard deviation of $\sigma_{k,i}$,

$x_i^{\min}, x_i^{\max}$ the minimum and maximum value of the *i*th variables,

f_k the fitness value of the *k*th individual,

$f_{\max}$ the maximum fitness value of the parent population,

a a positive constant which is less than one, and

g the number of present iteration.

The fitness value will be given by using (15).

$$f_k = Kf * F \quad (15)$$

Where

f_k fitness value of kth individual, and

Kf set as 1.

The tournament scheme is used for selection method which can be computed from (16) and (17)

$$w_t = \begin{cases} 1 & if \quad f_k > f_r \\ 0 & otherwise \end{cases} \quad (16)$$

$$s_k = \sum_{t=1}^{Nt} w_t \quad (17)$$

Where

w_t the weight value of each opponent,

f_k the fitness value of the *k*th individual,

f_r the fitness of the *r*th opponent randomly selected from the combined population based on $r = \lfloor 2*P*u+1 \rfloor$,

$\lfloor x \rfloor$ the greatest integer less than or equal *x*,

u uniform random in the interval [0,1],

P population size,

s_k the total score of each *k*th individual, and

Nt the number of opponents.

3.2. Modified EP by using sine function

In this paper, EP is modified by placing sin value from sin wave function into the mutation process. This modified algorithm is named modified EP/sin. The aim of this modified EP/sin is to step over local area. According to the $N(0, \sigma_{k,i}^2)$ of equation (13), the possible value is only positive. The parameter value is only increasing. The values from the sine function can be in positive and negative. This is the difference. And the meaning is valued from the sine function have more flexible. The parameter value of modified EP/sin can be increased and decreased up to the positive or negative values. This makes chances to step over the local area for optimal answers. The sine curve is shown in fig 2.

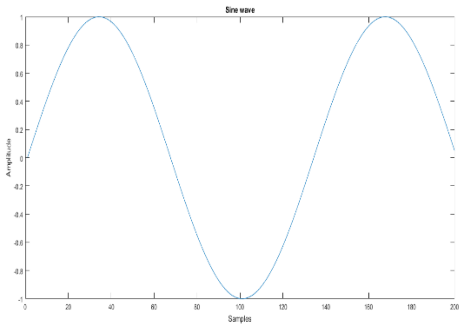

Fig 2. Sine curve

The mutation of modified EP/sin is (18).

$$x'_{k,i} = x_{k,i} + \left(\sin_{gen} \times N\left(0, \sigma_{k,i}^2\right)\right) \quad (18)$$

Where

$\sin_{gen}$ sine value of current iteration.

In addition, each individual contains system variables and parameters of UPFC. The real number is used for each variable. The *k*th individual is represented by a trial solution vector as (19).

$$V_k^T = [P_{Gi}, V_{Gi}, P_{Di}, Loc_i, PM_i] \quad (19)$$

Where

V_k^T trial vector of each individual,

P_{Gi} the real power of *i*th generator excluding generator of the slack bus,

V_{Gi} voltage magnitude of the *i*th generator,

P_{Di} the real power of load bus at bus *i*,

Loc_i locations of *i*th UPFC, and

PM_i parameter of *i*th UPFC.

4. Case study and experimental results

The IEEE 30-bus test system is used to demonstrate optimal allocation of UPFC for simultaneously F_1 and F_2 objective functions. The individual number of EP is set to 30. The maximum iteration is set to 100. Each batch contents 10 runs to determine minimum, average, and maximum value. Base case TTC is 164.30 MW. The IEEE 30-bus test system is shown in Fig. 3 [47].

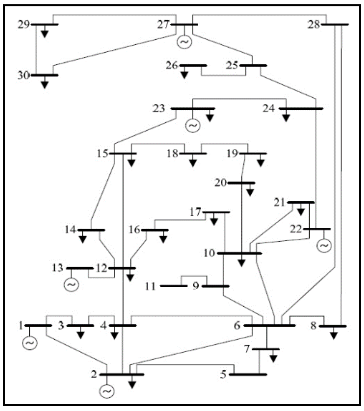

Fig.3 IEEE 30-bus test system

The voltage and angle limits of UPFC are $0 \le V_{Ui} \le 0.1$ pu. and $-\pi \le \alpha_{Ui} \le \pi$ radian, respectively. The number of UPFC is 1. The individual number of original EP and modified EP/sin are set to 30. The maximum iteration is set to 200.

4.1 Case1: Maximize TTC

In this case, the F_1 objective function is applied. The TTC included losses is determined by using the Newton-Raphson method. The minimum, average, and maximum TTC with UPFC installation are higher than those from the original EP with UPFC installation. Modified EP/sin gives the maximum enhance TTC 97.59% from base case TTC. This modified EP/sin can push the value of each variable step over the local area which enhances maximum TTC. Moreover, the system can be operated without any violence. The minimum, average, and maximum TTC are shown in Table I.

TABLE I Min, average, and max TTC from original EP with UPFC and modified EP/sin with UPFC

	Min TTC (MW)	Avg. TTC (MW)	Max TTC (MW)	STD (MW)
Original EP with UPFC	268.5700	278.5481	290.6410	7.5155
modified EP/sin with UPFC	302.0270	312.2820	324.6520	8.2302

The parameter of UPFC is Au and Vu. Au is the angle of UPFC. The Vu is the voltage per unit of voltage of UPFC. The optimal location of this result is line number 10. This line connects bus number 6 and number 8. The radian of UPFC is 0.7428 radian. The voltage per unit of UPFC is 0.0118. The optimal allocation of UPFC for max TTC from modified EP/sin is shown in Table II.

TABLE II Optimal allocation of UPFC for max TTC from modified EP/sin

Location	Parameter	
Line 10	Au (rad)	Vu (pu.)
	0.7428	0.0118

4.2 Case2: Maximization TTC per ED

In this case, F_2 objective function is applied. The TTC included losses is determined by using the Newton-Raphson method. The fuel cost is calculated by using the real power of generator and generator co-efficient. The generator co-efficiency is shown in Table III [16].

TABLE III Generator co-efficiency of IEEE 30-bus system

Unit	a_i ($/MWh)^2	b_i ($/MWh)	c_i ($/h)
1	0.0200	2.00	0
2	0.0175	1.75	0
3	0.0250	3.00	0
4	0.0625	1.00	0
5	0.0250	3.00	0
6	0.0083	3.25	0

The average and maximum TTC/ED from modified EP/sin with UPFC installation are higher than those from the original EP with UPFC installation in 0.90% and 2.8%, respectively. This result shows that the ability of modified EP/sin can determine the optimal allocation of UPFC which can improve TTC/ED without any violence. The minimum, average, and maximum TTC/ED are shown in Table IV.

TABLE IV Min, average, and max fuel cost from original EP with UPFC and modified EP/sin with UPFC

	Minimum TTC/ED (MWh/$)	Average TTC/ED (MWh/$)	Maximum TTC/ED (MW/$)	STD TTC/ED (MWh/$)
Original EP with UPFC	0.199	0.218	0.243	0.185
modified EP/sin with UPFC	0.190	0.220	0.250	0.191

TTC and ED of modified EP/sin with UPFC installation are shown in Table V.

TABLE V TTC and ED of modified EP/sin with UPFC installation

TTC (MW)	ED ($/h)
275.845	1105.507

The optimal location of this result is line number 10. This line connects bus number 6 and number 8. The radian of UPFC is 2.699 radian. The voltage per unit of UPFC is 0.0209. The optimal allocation of UPFC for max TTC from modified EP/sin is shown in Table VI.

TABLE VI Optimal allocation of UPFC for min fuel cost from modified EP/sin

Location	Parameter	
Line 10	Au (rad)	Vu (pu.)
	2.6999	0.0209

5. Conclusion

According to the contents, the original EP is modified by placing values from the sine function in the mutation method. This proposed method is used to determine the optimal allocation of UPFC to enhance TTC and maximize TTC/ED. Test results show that this modified EP/sin can determine the optimal allocation of UPFC which can enhance TTC to the maximum and maximize TTC/ED. These can be indicated that the using of modified EP/sin with the installation of UPFC will be profitable and worthwhile sustainable for the operating of the electrical power system.

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