Optimal Location and Optimal Power Flow with Interline Power Flow Controller Using Harmony Search algorithm

ตำแหน่งที่เหมาะสมของตัวควบคุมการไหลกำลังไฟฟ้าระหว่างสายและการไหลของกำลังไฟฟ้าที่เหมาะสมสำหรับระบบที่มีการติดตั้งตัวควบคุมการไหลกำลังไฟฟ้าระหว่างสาย โดยใช้วิธีการค้นหาความบรรสาน

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ABSTRACT

Interline power flow controller (IPFC) is a new concept of the Flexible AC transmission system (FACTS) device which can be used to control power flows of multiple transmission line. This paper present the optimal location for install IPFC has objective function is the maximum power inject from IPFC and optimal power flow when the installed IPFC at the best location has objective function is the minimum cost of generating electric power. The harmony search algorithm (HS) has been used to find the best location for install IPFC compare with genetic algorithm (GA) and particle swarm optimization (PSO). Finally, to find the optimal power flow when the install IPFC at the best location compare with install IPFC at the worst location and system in not installed IPFC.

บทคัดย่อ

ตัวควบคุมการไหลกำลังไฟฟ้าระหว่างสาย (IPFC) เป็นอุปกรณ์ตัวใหม่ของอุปกรณ์ยืดหยุ่นในระบบส่งจ่ายกำลังไฟฟ้ากระแสสลับ(FACTS)ซึ่งสามารถควบคุมการไหลของกำลังไฟฟ้าได้ดีกับระบบที่มีสายส่งจำนวนมาก โดยที่ในบทความนี้จะนำเสนอการตำแหน่งที่ดีที่สุดในการติดตั้ง IPFC โดยมีฟังก์ชันวัตถุประสงค์คือกำลังไฟฟ้าที่ IPFC สามารถฉีดเข้ามาในระบบได้มากที่สุด และการหาการไหลของกำลังไฟฟ้าที่เหมาะสมที่สุดเมื่อทำระบบทำการติดตั้ง IPFCที่ตำแหน่งที่ดีที่สุด โดยมีฟังก์ชันวัตถุประสงค์คือ ค่าใช้จ่ายในการผลิตกำลังไฟฟ้าของเครื่องกำลังไฟฟ้า ซึ่งการค้นหาความบรรสาน (HS)จะถูกใช้ในการหาตำแหน่งที่ดีที่สุดเปรียบเทียบวิธีการจีเนติกอัลกอริทึม (GA)และวิธีการค้นหาเชิงฝูงอนุภาค(PSO) เมื่อได้ตำแหน่งที่ดีที่สุดแล้วจะทำการหาการไหลที่เหมาะสมที่สุดเมื่อระบบติดตั้ง IPFCที่ตำแหน่งที่ดีที่สุดโดยใช้วิธีการ HS เปรียบเทียบกับ เมื่อระบบติดตั้ง IPFCที่ตำแหน่งที่แย่ที่สุด และ ระบบไม่มีการติดตั้ง IPFC

Key Words: Flexible AC transmission system (FACTS), Interline power flow controller (IPFC), Harmony search (HS)

คำสำคัญ:อุปกรณ์ยืดหยุ่นในระบบส่งจ่ายกำลังไฟฟ้ากระแสสลับตัวควบคุมการไหลกำลังไฟฟ้าระหว่างสายการค้นหาความบรรสาน

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Introduction

Recently, the deregulation of the electricity system became a significant problem in many countries do to increase in demand for electric power and other reasons. The FACTS devices has been widely regarded as power injection controller more competitive energy market. These are FACTS controller are used to improve the control active and reactive power flow. The main advantage of FACTS devices this strengthen the flexibility of the system and to increase capacity in the supply of power transmission system (Abdel-Moamen et al., 2003).

Of all model FACTS devices, the combined compensators for example IPFC and unified power flow controller (UPFC) accepted that it is equipped with the most powerful and diversity function applications. Also found, in the past, there have been attempts to create a model of UPFC for power flow analysis. However, UPFC is intended to offset a single transmission line, whereas the IPFC will control power flow of multi-line for transmission system (Bansal et al., 2010). Generally, IPFC it is composed of voltage sourced converters (VSC) connected in series with transmission line. For capable of control the power flow in multiple transmission line by using VSC connected together through DC link, which in verse each of the IPFC are able to inject active power and reactive power to the connected transmission line independently and facilitate active power transfer in transmission line connected (singh et al., 2010; Narainet al., 2000 and Noroozian et al., 1997).

In this paper present the application of HS algorithm was used in order to find out optimal location of IPFC and optimal power flow when the system install IPFC at the best location compare GA and PSO. However, the optimal power flow when system install IPFC at the best location will to compare system install IPFC at the worst location and is not to system install IPFC, where objective function is the cost of generating electric power. The optimal location of IPFC as presented in section optimal location of IPFC and optimal power flow when system install IPFC as presented in section optimal power flow with IPFC.

Interline Power Flow Controller Model

The interline power flow controller (IPFC), addresses the problem of compensating a number of transmission line at a given substation. Conventionally, series capacitive compensation (fixed, thyristor-controlled or SSSC-based) is employed to increase the transmittable real power over a given line and also to balance the loading of a normally encountered multiline transmission system. However, independent of their means of implementation, series reactive compensators are unable to control the reactive power flow in, and thus the proper load balancing of, the lines. The IPFC scheme, together with independently controllable reactive series compensation of each individual line, provides a capability to directly transfer real power between the compensated lines. This capability makes it possible to: equalize both real and reactive power flow between the lines; reduce the burden of overloaded line by real power transfer: compensate against resistive line voltage drops and the corresponding reactive power demand; and increase the effectiveness of the overall compensating system for dynamic disturbances. In other words, the IPFC can potentially provide a highly effective scheme for power transmission management at a multiline substation (Gyugyi et al., 1999).

A mathematical model for IPFC which will be referred to as power injection model is derived. This model is helpful in understanding the impact of the IPFC on the power system in the steady state. Furthermore, the IPFC model can easily be incorporated in the power flow model. Usually, in the steady state analysis of power systems, the VSC may be represented as a synchronous voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle.

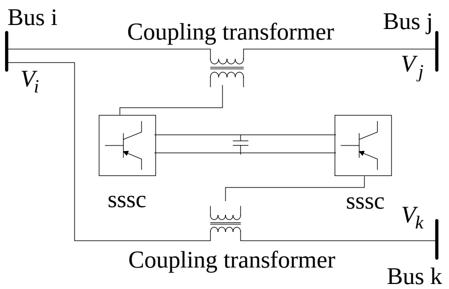

Figure 1 Schematic representation of a two converter IPFC

Basically, IPFC consist SSSC devices ranging from 2 or more, the SSSC each are connected together by used DC link as is shown inFigure1. In addition, active power can be exchanged through these two series VSC via the common DC link in IPFC. The combination of series connected VSC can inject a voltage magnitude and phase angle at the fundamental frequency while the DC link voltage can be maintained at a desired level. The DC link is represented to exchange active power between voltage sources.

A phasor diagram of system 1 as is shown in Figure 2. Define the relationship between V_i (sending end-voltage), V_j (receiving end-voltage), V_x(the voltage across x) and the inject voltage from IPFC $Vse_{ij}$with controllable magnitude ($0 \le Vse_{ij} \le Vse_{ij,\max}$) and angle θse_{ij} with controllable angle ($0 \le \theta se_{ij} \le 360^{\circ}$). The inserted voltage phasor Vse_{ij} to produce the effective sendind-end voltage $V_{seff} = V_i + Vse_{ij}$. The difference, $V_{seff} - V_j$, provides the compensated votage V_x. As angle θse_{ij} is varied over its full 360 degree.

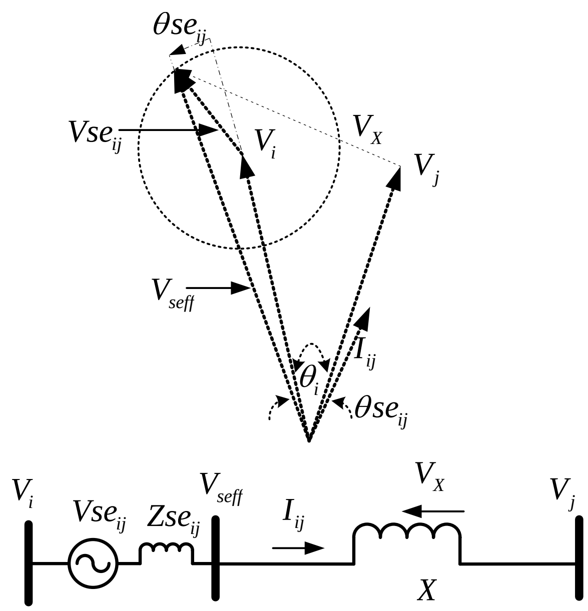

Figure 2 Phasor diagram of voltage control

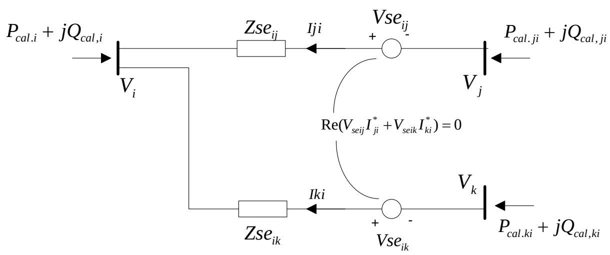

Figure 3 Equivalent circuitofIPFC

As for IPFC, the two VSCs are connected in series with two lines as shown in Figure 3. V_i ,V_j and V_k are complex voltage ant bus i, j and k Vse_{ij} ,Vse_{ik} are the controllable complex voltage of the two synchronous voltage sources, Zse_{ij} ,Zse_{ik} are the series transformer impedance, $P_{cal,i}$ and $Q_{cal,i}$ are the transmitted active and reactive power through the two branches of IPFC leaving bus i . $P_{cal,j}$ $P_{cal,k}$ and $Q_{cal,j}$ $Q_{cal,k}$ are the transmitted active and reactive power through the two branches of IPFC leaving bus *j, k* respectively. Active power can be transferred from one line to the other via the common dc link.

Based on the above equivalent circuit, the power flow equations at each bus are (Zhang et al., 2003).

$$P_{cal,i} = V_i^2 g_{ii} - \sum_{n=j,k} V_i V_n \left(g_{in} \cos(\theta_i - \theta_n) + b_{in} \sin(\theta_i - \theta_n) \right) - \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in} \cos(\theta_i - \theta_{se_{in}}) + b_{in} \sin(\theta_i - \theta_{se_{in}}) \right) \quad (1)$$

$$Q_{cal,i} = -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n \left(g_{in} \sin(\theta_i - \theta_n) - b_{in} \cos(\theta_i - \theta_n) \right) - \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in} \sin(\theta_i - \theta_{se_{in}}) - b_{in} \cos(\theta_i - \theta_{se_{in}}) \right) \quad (2)$$

where $n = j,k$

$$g_{in} + b_{in} = \frac{1}{Z_{se_{in}}} = Y_{se_{in}} \text{ , } g_{ii} = \sum_{n=j,k} g_{in} \text{ , } b_{ii} = \sum_{n=j,k} b_{in}$$

Assuming lossless converter valves, the active power supplied to one converter equals the active power demanded by the other, if there are no underlying storage systems; that is

$$\mathrm{Re}(Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*) = 0 \quad (3)$$

Or

$$\sum_{n=j,k} \{ Vse_{in}^2 g_{in} - V_i Vse_{in} \begin{pmatrix} g_{in} \cos(\theta_i - \theta se_{in}) \\ -b_{in} \sin(\theta_i - \theta se_{in}) \end{pmatrix} + V_n Vse_{in} \left(g_{in} \cos(\theta_i - \theta se_{in}) - b_{in} \sin(\theta_i - \theta se_{in}) \right) \} = 0 \quad (4)$$

where $n = j,k$

From equation (1)-(2) are identical to the conventional power flow equations of transmission lines. The remaining parts can be regarded as the power injections of the IPFC series sources, leading to the injection model of IPFC shown in Figure 4.

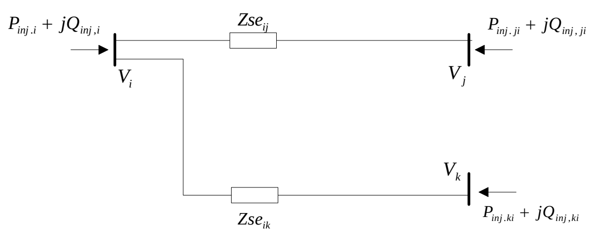

Figure4 Injection model of IPFC

$$P_{inj,i} = \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in} \cos(\theta_i - \theta_{se_{in}}) + b_{in} \sin(\theta_i - \theta_{se_{in}}) \right) \quad (5)$$

$$Q_{inj,i} = \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in} \sin(\theta_i - \theta_{se_{in}}) - b_{in} \sin(\theta_i - \theta_{se_{in}}) \right) \quad (6)$$

$$P_{inj,n} = -V_n V_{se_{in}} \left(g_{in} \cos(\theta_i - \theta_{se_{in}}) + b_{in} \sin(\theta_i - \theta_{se_{in}}) \right) \quad (7)$$

$$Q_{inj,n} = -V_n V_{se_{in}} \left(g_{in} \sin(\theta_i - \theta_{se_{in}}) - b_{in} \cos(\theta_i - \theta_{se_{in}}) \right) \quad (8)$$

where $n = j,k$

Optimal location of IPFC

In to find the optimal location of IPFC, will to determination install IPFC at all buses in system network. Where, installed in each location is to find the maximum power inject from IPFC. After that, select a location to installed can be maximum power inject from IPFC (also known as the best location).

Maximum $f(x)$

subject $g(x) = 0$, equality constraints

$h(x) \geq 0$, inequality constraints

By converting both equality and inequality constraints into penalty terms and therefore added to from the penalty function as described in the following equations.

$$P(x) = f(x) + \Omega(x) \quad (9)$$

$$\Omega(x) = \rho\left\{g^2(x) + [\max(0, h(x))]^2\right\} \quad (10)$$

Where $P(x)$ is the penalty function.

$\Omega(x)$ is the penalty term.

ρ is the penalty factor.

Using a concept of the penalty method (Ratniyomchai et al., 2010 and Dutta et al., 2006), the constrained optimization problem is transformed into an unconstrained optimization problem in which the penalty function as described above is minimized. Find maximum value can be returned by putting a minus before penalty term.

Objective function for optimal location IPFC

Objective function is the maximum transmitted active and reactive power through the two branches of IPFC leaving bus i (Karthik et al., 2012)is calculated by using the following equations.

$$P_{cal,i} = V_i^2 g_{ii} - \sum_{n=j,k} V_i V_n \left(g_{in}\cos(\theta_i - \theta_n) + b_{in}\sin(\theta_i - \theta_n)\right) - \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in}\cos(\theta_i - \theta_{se_{in}}) + b_{in}\sin(\theta_i - \theta_{se_{in}})\right) \quad (11)$$

$$Q_{cal,i} = -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n \left(g_{in}\sin(\theta_i - \theta_n) - b_{in}\cos(\theta_i - \theta_n)\right) - \sum_{n=j,k} V_i V_{se_{in}} \left(g_{in}\sin(\theta_i - \theta_{se_{in}}) - b_{in}\cos(\theta_i - \theta_{se_{in}})\right) \quad (12)$$

Equality constraintsfor optimal location IPFC

Equality constraints are the lossless converter valves, the active power supplied to one converter equals the active power demanded by the other, if there are no underlying storage systemsis calculated by using the following equations.

$$\mathrm{Re}(Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*) = 0 \quad (13)$$

Or

$$\sum_{n=j,k} \{Vse_{in}^2 g_{in} - V_i Vse_{in} \begin{pmatrix} g_{in}\cos(\theta_i - \theta se_{in}) \\ -b_{in}\sin(\theta_i - \theta se_{in}) \end{pmatrix} + V_n Vse_{in}\left(g_{in}\cos(\theta_i - \theta se_{in}) - b_{in}\sin(\theta_i - \theta se_{in})\right)\} = 0 \quad (14)$$

where $n = j, k$

Inequality constraintsfor optimal location IPFC

Inequality constraints are the variable limitations of VSCs in IPFC is calculated by using the following equations.

$$Vse_{in}^{\min} \le Vse_{in} \le Vse_{in}^{\max} \quad (15)$$

$$\theta se_{in}^{\min} \le \theta se_{in} \le \theta se_{in}^{\max} \quad (16)$$

$Vse_{in}^{\min}, Vse_{in}^{\max}$ upper and lower voltage of IPFC at bus n

$\theta se_{in}^{\min}, \theta se_{in}^{\max}$ upper and lower angle of IPFC at bus n

Where $n = j, k$

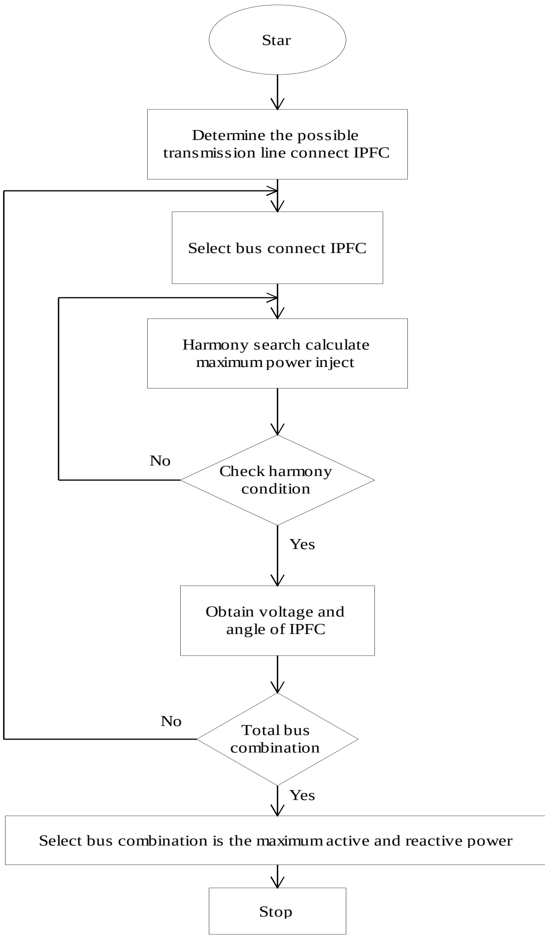

Figure5 flowchart of optimal location IPFC using HS

The penalty function can be formulated as follows.

$$P(x) = f(x) - \Omega_{loss} - \Omega_{Vse} - \Omega_{\theta se} \quad (17)$$

Where

$$\Omega_{loss} = \rho \sum_{n=j,k} \{Vse_{in}^2 g_{in} - V_i Vse_{in} \left(g_{in} \cos(\theta_i - \theta se_{in}) - b_{in} \sin(\theta_i - \theta se_{in}) \right) + V_n Vse_{in} \left(g_{in} \cos(\theta_i - \theta se_{in}) - b_{in} \sin(\theta_i - \theta se_{in}) \right)\}^2 \quad (18)$$

$$\Omega_{Vse} = \rho \sum_{n=j,k} \{\max(0, Vse_{in} - Vse_{in}^{\max})\}^2 + \rho \sum_{n=j,k} \{\max(0, Vse_{in}^{\min} - Vse_{in})\}^2 \quad (19)$$

$$\Omega_{\theta se} = \rho \sum_{n=j,k} \{\max(0, \theta se_{in} - \theta se_{in}^{\max})\}^2 + \rho \sum_{n=j,k} \{\max(0, \theta se_{in}^{\min} - \theta se_{in})\}^2 \quad (20)$$

Optimal power flow with IPFC

In this section, optimal power flow with IPFC. It is common to choose active power generation cost as the objective function to be minimized, because economic aspects are very important in power system. It the power system with IPFC, injection active and reactive power from IPFC will equate to a synchronous voltage source injecting. The optimal power flow problem is a nonlinear optimization problem can be formulated as follows.

Minimum $f(x)$

subject $g(x) = 0$, equality constraints

$h(x) \geq 0$, inequality constraints

Objective function for optimal power flow with IPFC

Although most of commonly used objective in the optimal power flow problem formulation is the minimization of the total cost of real power generation (Oonsivilai et al., 2009). In this paper, costs of each generating unit are assumed to be function, only of the active power generation and are represented by quadratic-polynomial, the objective function is calculated by using the following equations.

$$Min \quad F_T = f(P_{G,i}) = \sum_{i=1}^{N_G} (a_i + b_i P_{G,i} + C_i P_{G,i}^2) \quad (21)$$

Where

N_G number of generators.

a_i, b_i, c_i coefficients of fuel cost $f(P_{G,i})$

$P_{G,i}$ active power of generator at bus i

$f(P_{G,i})$ the fuel cost of generating unit i

Equality constraints for optimal power flow with IPFC

Equality constraints for optimal power flow with flexible ac transmission (FACTs) problem (Wood A.J, el al (1996); Kwang Y.Lee., et al (2008)), reflecting the nature of the power system according load flow equation, the power production at bus generator combined with power inject from IPFC (equation 5-8) equal the demand of load. The equality constraints calculated by using the following equations.

$$P_{G,i} + \sum_{m=i,j,k} P_{inj,m} - P_{D,i} - \sum_{j=1}^{N_B} \left| Y_{i,j} V_i V_j \right| \cos(\theta_{i,j} - \delta_i + \delta_j) = 0 \quad (22)$$

$$Q_{G,i} + \sum_{m=i,j,k} Q_{inj,m} - Q_{D,i} + \sum_{j=1}^{N_B} \left| Y_{i,j} V_i V_j \right| \sin(\theta_{i,j} - \delta_i + \delta_j) = 0 \quad (23)$$

Where

$i = 1, 2, 3, ..., N_B$: N_B is the number of buses

$P_{G,i}$ is the real power generator at bus i

$Q_{G,i}$ is the reactive power generator at bus i

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

$P_{inj,m}$ is the real power inject from IPFC at bus m

$Q_{inj,m}$ is the reactive power inject from IPFC at bus m

$\theta_{i,j}$ is the angle of bus admittance element i, j

$Y_{i,j}$ is the magnitude of bus admittance element i, j

Inequality constraints for optimal power flow with IPFC

Inequality constraintsfor optimal power flow problem, reflecting the limit of the device in power system: system security constraints, i.e. transmission lines loading, generator security constraints, i.e. real and reactive power output. The inequality constraints calculated by using the following equations (Oonsivilai et al., 2009).

$$P_{G,i}^{\min} \le P_{G,i} \le P_{G,i}^{\max} \quad ; \quad i = 1, 2, 3, ..., N_G \quad (24)$$

$$Q_{G,i}^{\min} \le Q_{G,i} \le Q_{G,i}^{\max} \quad ; \quad i = 1, 2, 3, ..., N_G \quad (25)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad ; \quad i = 1, 2, 3, ..., N_B \quad (26)$$

$$Q_{comp,i}^{\min} \le Q_{comp,i} \le Q_{comp,i}^{\max} \quad ; \quad i = 1, 2, 3, ..., N_C \quad (27)$$

$$T_i^{\min} \le T_i \le T_i^{\max} \quad ; \quad i = 1, 2, 3, ..., N_T \quad (28)$$

Where

$V_i^{\min}, V_i^{\max}$ upper and lower of voltage magnitude at bus i

$P_{G,i}^{\min}, P_{G,i}^{\max}$ upper and lower of real power by generator at bus i

$Q_{G,i}^{\min}, Q_{G,i}^{\max}$ upper and lower of reactive power by generator at bus i

$Q_{comp,i}^{\min}, Q_{comp,i}^{\max}$ upper and lower of reactive power source at bus i

$T_i^{\min}, T_i^{\max}$ upper and lower of tap position of transformer at bus i

The penalty function can be formulated as follows.

$$P(x) = f(x) + \Omega_P + \Omega_Q + \Omega_C + \Omega_T + \Omega_V + \Omega_G + \Omega_{QG} \qquad (29)$$

Where

$$\Omega_P = \rho \sum_{i=1}^{N_B} \left\{ \begin{array}{l} P_{G,i} + \sum_{m=i,j,k} P_{inj,m} - P_{D,i} \\ - \sum_{j=1}^{N_B} \left| Y_{i,j} V_i V_j \right| \cos(\theta_{i,j} - \delta_i + \delta_j) \end{array} \right\}^2 \qquad (30)$$

$$\Omega_Q = \rho \sum_{i=1}^{N_B} \left\{ \begin{array}{l} Q_{G,i} + \sum_{m=i,j,k} Q_{inj,m} - Q_{D,i} \\ + \sum_{j=1}^{N_B} \left| Y_{i,j} V_i V_j \right| \sin(\theta_{i,j} - \delta_i + \delta_j) \end{array} \right\}^2 \qquad (31)$$

$$\Omega_C = \rho \sum_{i=1}^{N_C} \{\max(0, Q_{comp,i} - Q_{comp,i}^{\max})\}^2 + \rho \sum_{i=1}^{N_C} \{\max(0, Q_{comp,i}^{\min} - Q_{comp,i})\}^2 \qquad (32)$$

$$\Omega_T = \rho \sum_{i=1}^{N_T} \{\max(0, T_i - T_i^{\max})\}^2 + \rho \sum_{i=1}^{N_T} \{\max(0, T_i^{\min} - T_i)\}^2 \qquad (33)$$

$$\Omega_V = \rho \sum_{i=1}^{N_B} \{\max(0, V_i - V_i^{\max})\}^2 + \rho \sum_{i=1}^{N_B} \{\max(0, V_i^{\min} - V_i)\}^2 \qquad (34)$$

$$\Omega_G = \rho \sum_{i=1}^{N_G} \{\max(0, P_{G,i} - P_{G,i}^{\max})\}^2 + \rho \sum_{i=1}^{N_r} \{\max(0, P_{G,i}^{\min} - P_{G,i})\}^2 \qquad (35)$$

$$\Omega_{QG} = \rho \sum_{i=1}^{N_G} \{\max(0, Q_{G,i} - Q_{G,i}^{\max})\}^2 + \rho \sum_{i=1}^{N_G} \{\max(0, Q_{G,i}^{\min} - Q_{G,i})\}^2 \qquad (36)$$

Where

N_G is the total number of generators.

N_C is the total number of reactive power sources.

N_T is the total number of transformers.

Harmony search algorithm

The harmony search algorithm (Sinsupan el al., 2010) wasconceptualized from the musical process ofsearching for a 'perfect state' of harmony, such asjazz improvisation. Musical performances seek a best state (fantastic harmony) determined by aesthetic estimation, as the optimization algorithms seek a best state (global optimum—minimum cost or maximum benefit or efficiency) determined by objective function evaluation. Aesthetic estimation is determined by the set of the sounds played by joined instruments, just as objective function evaluation is determined by the set of the values produced by component variables; the sounds for better aesthetic estimation can be improved through practice after practice, just as the values for better objective function evaluation can be improved iteration by iteration.

The new algorithm is named Harmony Search (HS) and the steps in the procedure of HS are as follows (Zong et al., 2001):

Steps 1: Construct harmony memory size in order to store

them in harmony memory (HM).

$$HM = \left\langle \begin{array}{ccc|c} x_1^1 & \cdots & x_n^1 & f(x^1) \\ \vdots & \ddots & \vdots & \vdots \\ x_1^{hms} & \cdots & x_n^{hms} & f(x^{hms}) \end{array} \right\rangle$$

Where hms is the harmony memory size.

n is the total variable.

Step 2: Improvise a new harmony from HM.

Step 3: If the new harmony is better than minimum harmony in HM, include the new harmony in

HM, an exclude the minimum harmony from HM.

Step 4: If stopping criteria are not satisfied, go to Step 2.

Result and discussion

In MATLAB 2013a platform, the planned technique is implemented and it is tested on IEEE-14 bus system. The tested IEEE 14 BUS system is obtained from http://www.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm. The diagram of the tested bus system is shown in Figure 6.

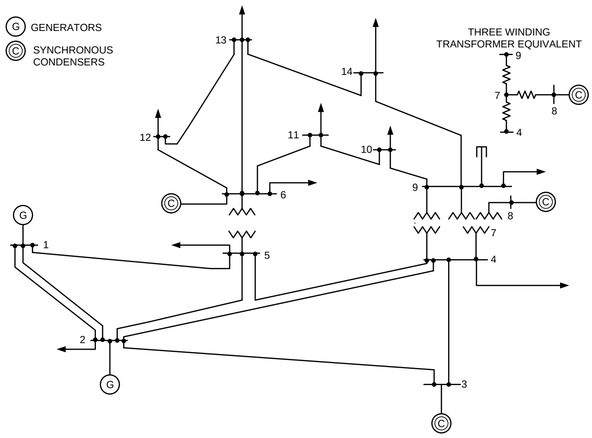

Figure6 IEEE-14 bus system

The tested using harmony search algorithm, is divided into 4 test cases together.

Case 1: optimal location IPFC using harmony search algorithm compare with PSO and GA.

Case 2: optimal power flow without IPFC using harmony search algorithm.

Case 3: optimal power flow with IPFC at position worst power inject from IPFC (from case 1) using harmony search algorithm.

Case 4: optimal power flow with IPFC at position best power inject from IPFC (from case 1) using harmony search algorithm.

Case 1

Find optimal location IPFC using harmony search algorithm compare with PSO and GA. Find maximum power at bus combination, be tested all bus in power system results as is shown in figure 7, then select bus combination maximum power. Table 1 gave limit of variable used to be optimized.

Table 1 Limit variable of IPFC

Item	Limits variable
Vse_{ij} , Vse_{ik}	[0 , 0.1] pu.
θse_{ij} , θse_{ik}	[$-\pi$, π]
Zse_{ij} , Zse_{ik}	0.1 pu.

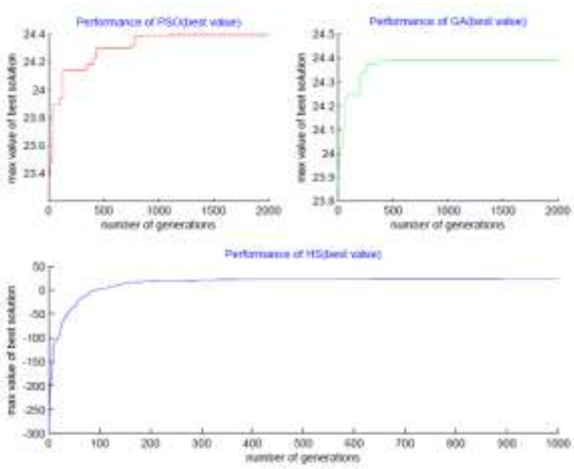

Figure 7 convergence curve for maximum power at bus install IPFC

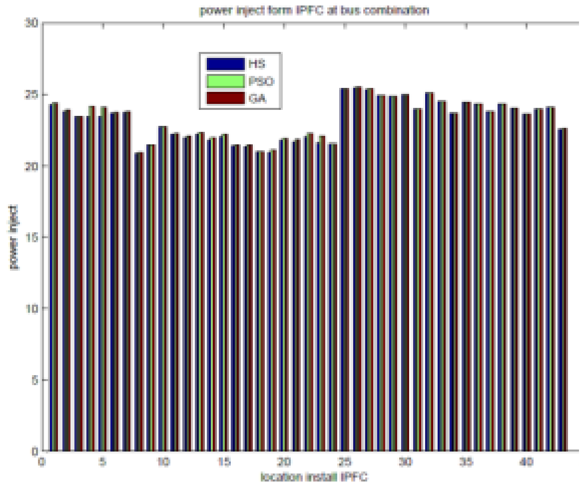

Figure8 Power inject of IPFC at various position in the system

From Figure8 at trials 26 will be the best power inject from IPFC (this location can be the maximum inject power from IPFC). Trials 26, location buses install IPFC equal 6-5 and 6-13. And trials 8 will be the worst power inject from IPFC. Trials 8location buses install IPFC equal 3-2 and 3-4. Table 2 is show optimal parameter for IPFC using HS at buses install IPFC.

Table 2 is the optimal parameter for IPFC at combinationbuses

IPFC combination between bus	Magnitude and angle of OPFC
6-5 6-13	$Vse_{ij} = 0.0990$ pu $Vse_{ik} = 0.0987$ pu $\theta se_{ij} = 2.0118$ pu $\theta se_{ik} = -2.6042$ pu
3-2 3-4	$Vse_{ij} = 0.0707$ pu $Vse_{ik} = 0.0975$ pu $\theta se_{ij} = -1.5638$ pu $\theta se_{ik} = 3.0056$ pu

The minimum and maximum amplitude of, active and reactive power of generators, reactive power of synchronous condensers, amplitude voltage of all bus, angle voltage of all bus and tap transformer given in Table 3.

Table 3 limit of control variables used for optimal power flow

Parameters control	Min	max
$P_{G,1}$	50 (MW)	300 (MW)
$P_{G,2}$	20 (MW)	40 (MW)

Table 3 limit of control variables used for optimal power flow (Cont.)

Parameters control	Min	max
$Q_{G,1}$	-60 (MVar)	100 (MVar)
$Q_{G,2}$	-40 (MVar)	50 (MVar)
$Q_{C,3}$	0 (MVar)	40 (MVar)
$Q_{C,6}$	-6 (MVar)	24 (MVar)
$Q_{C,8}$	-6 (MVar)	24 (MVar)
V at all buss	0.9 pu.	1.1 pu.
δ at all bus	-30 $^\circ$	30 $^\circ$
T tap transformers	0.9 pu.	1.1 pu.

Case 2

Is the optimal power flow without IPFC using HS algorithm. Find minimumcost of generating electric power, be tested in IEEE 14 BUS system. Table 4 is show the optimal parameter of optimal power flow for system is not to install IPFC. Figure 9as is show in the convergence curve of minimum Generation cost.

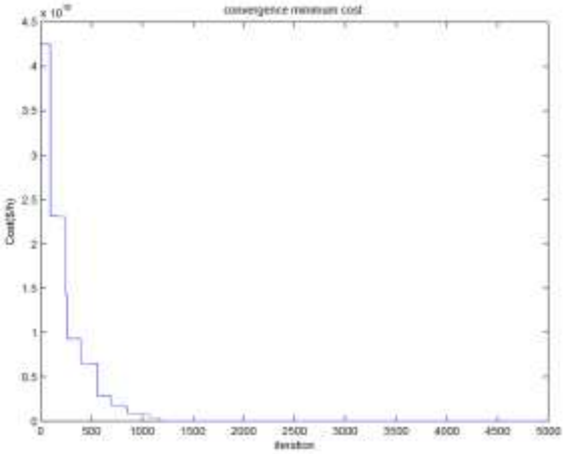

Figure9 convergence curve for minimum cost without IPFC

Table 4 is show the optimal parameter of optimal power flow of system is not to install IPFC

bus	Active power (MW)	Reactive power (MVar)	Voltage magnitude (pu)	Angle voltage (degreee)
1	281.989	91.241	0.921	0
2	29.198	45.883	1.001	-0.900
3		20.400	0.942	2.944
4			0.925	-5.429
5			1.046	-2.844
6		16.653	0.963	-3.364
7			0.977	-9.122
8		22.341	0.991	-17.533
9			0.907	-8.549
10			1.055	-12.689
11			1.047	-5.360
12			1.005	-6.496
13			0.920	-7.606
14			0.956	2.594
Tap transformer				
line 4-7 = 1.0310pu. line 4-9 = 0.9589 pu. line 5-6 = 0.9658 pu.				
Cost of generating electric power = $2.1997x10^3$ $/hr				

Case 3

Is theOptimal power flow with IPFC to install IPFC at the worst location (install IPFC between bus 3-2 and bus 3-4) using HS algorithm. Find minimumcost of generating electric power, be tested in IEEE 14 BUS system. Table 5is show the optimal parameter of optimal power flow for system install IPFC at between bus 3-2 and bus 3-4. Figure 10as is show in the convergence curve of minimum Generation cost.

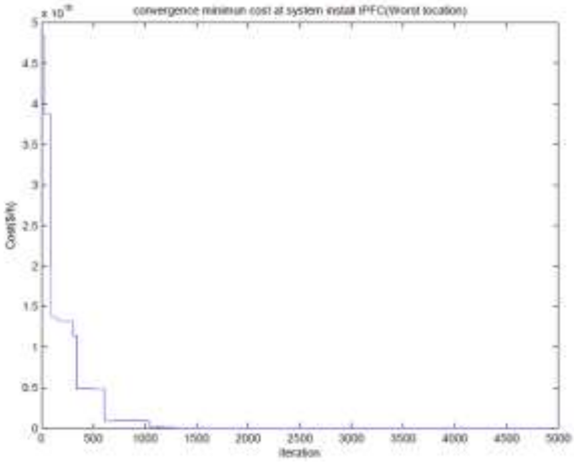

Figure 10 convergence curve for minimum cost with IPFC

Table 5 is show the optimal parameter of optimal power flow for system install IPFC at between bus 3-2 and bus 3-4

bus	Active power (MW)	Reactive power (MVar)	Voltage magnitude (pu)	Angle voltage (degreee)
1	280.944	77.363	1.002	0
2	26.594	39.753	0.951	-4.476
3		15.841	1.002	-5.514
4			0.944	-12.687
5			0.967	-6.264
6		15.836	0.931	-11.309
7			1.009	-15.045
8		16.289	1.036	-15.633
9			1.056	-14.944
10			0.968	-17.572
11			0.985	-14.260
12			0.939	-21.393
13			0.981	-7.644
14			0.963	-13.711
Tap transformer			Parameter of IPFC	
line 4-7 = 1.0802pu. line 4-9 = 1.0078 pu. line 5-6 = 0.9009 pu.			Vse_{ij} = 0.0707 pu Vse_{ik} = 0.0975 pu θse_{ij} = -1.5638 pu θse_{ik} = 3.0056 pu	
Cost of generating electric power = 2.1759×10^{3} \$/hr				

Case 4

Is theOptimal power flow with IPFC to install IPFC at the best location (install IPFC between bus 6-5 and bus 6-13) using HS algorithm. Find minimumcost of generating electric power, be tested in IEEE 14 BUS system. Table 6is show the optimal parameter of optimal power flow for system install IPFC at between bus 6-5 and bus 6-13. Figure 11as is show in the convergence curve of minimum Generation cost.

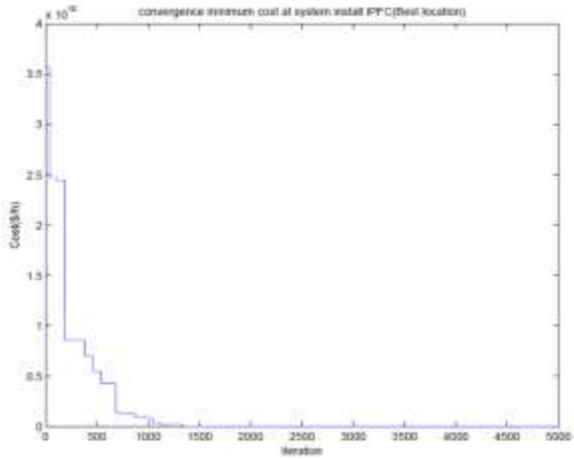

Figure 11 convergence curve for minimum cost with IPFC

Table 6 is show the optimal parameter of optimal power flow for system install IPFC at between bus 6-5 and bus 6-13

bus	Active power (MW)	Reactive power (MVar)	Voltage magnitude (pu)	Angle voltage (degreee)
1	265.994	70.399	1.042	0
2	24.228	38.711	0.955	-2.901
3		24.257	0.947	-6.605
4			0.931	-6.968
5			0.981	-4.533
6		4.403	0.971	-8.882
7			0.945	-8.710
8		-4.588	1.089	-10.531
9			0.914	-9.220
10			1.074	-9.411
11			0.925	-7.268
12			0.941	-11.671
13			0.983	-12.252
14			1.032	-14.664

Table 6is show the optimal parameter of optimal power flow for system install IPFC at between bus 6-5 and bus 6-13 (Cont.)

Tap transformer	Parameter of IPFC
line 4-7 = 0.9408pu. line 4-9 = 1.0802 pu. line 5-6 = 0.9416 pu.	Vse_{ij} = 0.0990 pu Vse_{ik} = 0.0987 pu θse_{ij} = 2.0118 pu θse_{ik} = -2.6042 pu
Cost of generating electric power = 2.0056×10^3 \$/hr	

Conclusions

Of standard IEEE 14 bus test system is shown. Installation Equipment IPFC the position between bus 3-2 and 3-4 to the cost incurred in the production of electrical power equal to 2.1759×10^3 \$/hr, which can reduce cost up to 24 \$/hr (case3 compare case2). Installation Equipment IPFC the position between bus 6-5 and 6-13will make the cost incurred in the production of electrical power equal to 2.0056×10^3 \$/hrwhich can reduce the cost was equal to 194 \$/hr (case 4 compare case2). Therefore, installation IPFC at the best location for the maximum power inject from IPFC, can be reduce the cost of generating power as much as possibleas is shown in Figure 12.

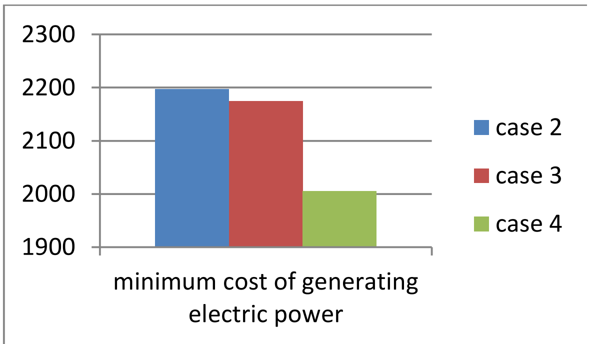

Figure 12 Production cost all 3 cases

Acknowledgements

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