Journal of Theoretical and Applied Information Technology
10th October 2014. Vol. 68 No.1

ISSN: **1992-8645** www.jatit.org E-ISSN: **1817-3195**

APPLYING THE *FVSI*-GENERATION TRACING AND HYBRID ANT COLONY ALGORITHM FOR EFFECTIVE STATIC GENERATION POWER DISPATCH

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ABSTRACT

This paper proposes the latest application of power tracing technique for voltage stability improvement. Instead of solving losses charge allocation problem in deregulated power market as performed by many researchers, the proposed technique can be implemented for effective static generation power dispatch; that is, by determining suitable generating units involved in re-dispatching with the aim of providing a more economical and effective power generation. Using power tracing approach, the determination of suitable generating units can be done by means of stability index tracing or specifically termed as Fast Voltage Stability Index-Generation Tracing (*FVSI*-GT). After deriving a ranking list of generator buses via *FVSI*-GT, the real and reactive power of the selected generators are sized using a new hybrid algorithm; the Blended Crossover Continuous Ant Colony Optimization (BX-CACO). Simulation and experiment on IEEE 57-Bus reliability test system (RTS) justified the reliability of *FVSI*-GT for precise selection of suitable generators besides other conventional ranking methods. In addition, the proposed BX-CACO showed a tremendous performance in terms of convergence speed and solution quality.

Keywords: *BX-CACO, FVSI-GT, Generation Power Dispatch, Stability Index Tracing*

1. INTRODUCTION

For a generation company (GENCO), scheduling the generated real and reactive power to be dispatched is a necessary task for effective power generation and transportation. Regarding the real power dispatch, the main aim is to reduce to fuel cost to be spent [1]. The lower the cost, the more effective the dispatch is. On the other hand, generating adequate reactive power is more to voltage stability point of view. In maintaining acceptable voltage level at all buses of a power system, an adequate reactive power support is critically demanded [2]. With the integration between good management of reactive power flow and sufficient reactive power support, a stable condition of the system can be acquired. Thus, based on such perspective, generation power dispatch is a task for determining suitable amount of real and reactive power to be injected by a GENCO with more economical and just enough to provide satisfactory stability performance of the system. From this point, it is revealed that performing generation power dispatch is not only about cost to be spent or economical things, but also the voltage stability condition. When talking about the countermeasure available at a generation site, the unit commitment (UC) and economic load dispatch (ELD) are the examples of generation power dispatch available to counteract any voltage instability that might lead to critically unwanted disturbances, such as voltage collapse. Previous works related to generation power dispatch concerning UC and ELD can be explored in [3-6]; including the method for the implementation of dynamic economic dispatch, short-term generation scheduling (STGS), security-constrained generation scheduling (SCGS), and optimization techniques. A two-sequential task of STGS was proposed by [7] combining the Evolutionary Algorithm (EA) and lambda iteration method. Sequentially, the use of EA was to provide a more economical power scheduling with the help of lambda iteration method for optimal generator's output power sizing. The results revealed that such approach gained benefit in terms of satisfactory cost to be spent and system performance. Later, reference [8] performed SCGS in a large scale power system considering dispatch constraints, network constraints, and security constraints for more practical experiment. As in [7], the research developed a two-sequential task algorithm for more effectiveness and reliability during verification on IEEE 118-Bus reliability test system (RTS). After experiment, the method was successful to achieve acceptable performance of SCGS with satisfactory computation time. A combinational generation power dispatch between UC and ELD was performed by [9] on thermal generating units. Taking into account a large-scale wind power system as the test system, the research utilized the forecasted wind output power in the developed algorithm for more reliability. Another combinational UC-ELD was proposed by [10] with the introduction of a novel double filtration technique for optimal performance. With the application of the immature ELD and look-forward rule, the research was able to obtain the optimal power dispatch by firstly determining the potential combination of generating units. After that, the Artificial Intelligence (AI) based optimization for solving ELD was proposed by [11] using Simulated Annealing (SA). The research treated the fuel cost and emission level as the objective functions to solve the problem in hydro-thermal power plant. It was justified that SA was applicable for practical applications as it gave global optimal solution with consistent and reliable results. Other AI optimization techniques were also useful in other researches concerning generation power dispatch. The Genetic Algorithm (GA) was applied in [12] for reducing the fuel cost and emission level, the Particle Swarm Optimization (PSO) in [13] for STGS, and lastly the Artificial Immune System (AIS) in [14] for combined heat and power ELD.

Meanwhile, the problem regarding electricity deregulation arises as some of the traditional techniques failed to establish fair and non discriminatory electricity market. Transaction based methods such as postage stamp rate, MW-mile methodology, and contractual path are the examples of traditional approach [15, 16]. After the weakness was encountered, for the first time, Bialek [17] proposed a novel approach for accurately determining the allocation of transmission usage charge using tracing technique; or commonly termed the power tracing. In this method, the generator and load contribution on losses and line flows were determined via upstream and downstream algorithms considering a lossless power system. After that, Kirschen *et al* [18] proposed an alternative power tracing technique using the concept of domain, common, and link. Without requiring the upstream and downstream algorithm as in [17], the tracing of generator contribution was performed based on state graph; that is, a simplified diagram of a power system consisting only of some commons connected by links. This has made the tracing process to be simpler as compared to that of Bialek. Next, Teng [19] applied circuit theory for developing a power tracing algorithm based on basic Ohm's Law. Contrary to the previous methods that can only trace either real or reactive power, the algorithm was able to trace the complex powers contributed by individual generator. However, the problem of negative sharing is still unavoidable. Optimization approach for allocating losses to individual generator was firstly proposed by Abhyankar *et al* [20] without requiring assumption like proportional sharing principal (PSP). Unfortunately, the proposed method was computationally burdensome since too many constraints have to be considered. The latest power tracing technique was proposed by Mustafa *et al* [21] and Hamid *et al* [22] using AI applications. In [21], the Support Vector Machine (SVM) incorporated with GA was utilized during prediction process; whereas, a hybrid ant colony algorithms was applied in [22] for fast and efficient optimization process. Nevertheless, the whole power tracing techniques are only for electricity deregulation so far. They are applicable just for solving non discriminatory transmission service pricing and there is no research tries to exploit the benefit of power tracing in other fields like voltage stability.

This paper proposes the latest application of power tracing technique for voltage stability improvement. Instead of solving deregulated market problems as what other researchers did; for the first time, the proposed power tracing technique can be implemented for effective static generation power dispatch. The proposed technique is implemented by determining the suitable generating units to undergo generation power dispatch using stability index tracing; namely, the Fast Voltage Stability Index – Generation Tracing (*FVSI*-GT). The ranking list obtained from *FVSI*-GT will be used to identify the appropriate generators based on their priority. After the suitable generators are selected, the sizing of their real and reactive output powers will be handled by a newly developed hybrid algorithm; i.e. the Blended Crossover Continuous Ant Colony Optimization (BX-CACO).

2. THE STABILITY INDEX TRACING AND ITS APPLICATIONS

This section presents the proposed stability index tracing applied for determining the suitable generating units to undergo generation power dispatch. There are two subsections to be presented. The first one demonstrates the modification of an original line-based stability index equation for the use in voltage stability field using the proposed stability index tracing; whereas, the second one illustrates the application of the proposed technique.

2.1 The Fast Voltage Stability Index-Generation Tracing (*FVSI*-GT)

Instead of tracing the magnitude of power as what other methods did, the proposed approach performs the tracing process based on stability index known as the Fast Voltage Stability Index (*FVSI*) for voltage stability application. The line-based stability index *FVSI* was proposed by Musirin [23] and it was justified in [24, 25] that the index is reliable for assessment of static voltage stability of a power system; which has motivated this research to utilize it as the index to be traced. A stress experienced by an *l*-th line can be expressed by *FVSI* as follows.

$$FVSI_l = \frac{4Z_l^2 Q_r}{V_s^2 X_l} \qquad (1)$$

Where,

$FVSI_l$: *FVSI* of *l*-th line
V_s : Sending end voltage
Q_r : Receiving end reactive power
Z_l : Line impedance
X_l : Line reactance

For a stable power system, all transmission lines must have *FVSI* less than 1.00. Otherwise, there will unwanted disturbances that might lead to voltage collapse or blackout.

In the field of power tracing, the term '*generation tracing*' signifies one of the power tracing tasks for tracing the losses and line flows contributed by individual generator of the system. Hence, when the contribution of generators in *FVSI* is needed to be traced, it is termed as *FVSI*-Generation Tracing (*FVSI*-GT). However, since *FVSI* is a line-based index, there is a need to modify the equation as in (1) for the purpose of stability index tracing. The modified version of *FVSI* equation via stability index tracing can be used to indicate the most sensitive bus instead of line. The concept of major contributor in power tracing will be utilized in the stability index tracing to identify the generator that becomes the major contributor of stress experienced by a certain transmission line. According to [20], a power to be traced can be expressed as a summation of individual contributed power by generators. By the same token, *FVSI* of *l*-th line can also be expressed as a summation of individual contributed *FVSI* by generators, as in (2).

$$FVSI_l = FVSI_l^1 + FVSI_l^2 + \ldots \\ \ldots + FVSI_l^k + \ldots + FVSI_l^{ngen} \qquad (2)$$

Where, $FVSI_l^{\,k}$ is the individual contributed *FVSI* by *k*-th generator or specifically termed as the traced *FVSI*, and *ngen* is the number of generators. Replacing (1) into (2) gives:

$$FVSI_l = \frac{4Z_l^2 Q_r^1}{V_s^2 X_l} + \frac{4Z_l^2 Q_r^2}{V_s^2 X_l} + \ldots \\ \ldots + \frac{4Z_l^2 Q_r^k}{V_s^2 X_l} + \ldots + \frac{4Z_l^2 Q_r^{ngen}}{V_s^2 X_l} \qquad (3)$$

$$FVSI_l = \frac{4Z_l^2}{V_s^2 X_l}(Q_r^1 + Q_r^2 + \ldots \\ \ldots + Q_r^k + \ldots Q_r^{ngen}) \qquad (4)$$

$$\therefore FVSI_l = \frac{4Z_l^2}{V_s^2 X_l} \sum_{k=1}^{ngen} Q_r^k \qquad (5)$$

Where, $Q_r^{\,k}$ is the receiving end power of *l*-th line contributed by *k*-th generator. Again, based on [20], the participation of *k*-th generator in the power to be traced is given in (6).

$$Q_r^k = x_r^k . Q_{Gk} \qquad (6)$$

Substituting (6) into (5) gives:

$$\therefore FVSI_l = \frac{4Z_l^2}{V_s^2 X_l} \sum_{k=1}^{ngen} x_r^k . Q_{Gk} \qquad (7)$$

Where, $x_r^{\,k}$ is the fraction of receiving end power shared by *k*-th generator, and Q_{Gk} is the reactive power generated by *k*-th generator. Through deduction, the traced *FVSI* of *l*-th line contributed by *k*-th generator can be calculated as in (8).

$$FVSI_l^k = \frac{4Z_l^2}{V_s^2 X_l}\left(x_r^k . Q_{Gk}\right) \qquad (8)$$

Hence, it is revealed that the traced *FVSI* can be determined by tracing the fraction of receiving end power, x_r^k via any power tracing methods discussed in the literature. Article [26] provides a complete presentation on how to perform *FVSI*-GT using the existing power tracing approaches.

2.2 Application of *FVSI*-GT for Generator Selection

By tracing *FVSI* contributed by individual generator using the *FVSI*-GT algorithm, the values of $FVSI_l^{\,k}$ will be used for deriving a ranking list indicating the priority of generator buses to be selected. Figure 1 presents a depiction of a simple 3-bus power system for explaining the usage of *FVSI*-GT. Assuming that the values of *FVSI* for two transmission lines (i.e. $FVSI_{1-2}$ and $FVSI_{2-3}$) have been calculated via (1), the traced *FVSI* values can be determine using the proposed *FVSI*-GT. After performing that, the traced *FVSI* values are indicated close to each generator in Figure 1. The symbol $FVSI_{1-2(G1)}$ means the traced *FVSI* of line between bus 1 and bus 2 contributed by generator at bus 1. If all the traced *FVSI* values of a certain line are summed together, the answer will be the value of *FVSI* for that line. For example; $FVSI_{1-2} = FVSI_{1-2(G1)} + FVSI_{1-2(G2)} + FVSI_{1-2(G3)} = 0.50 + 0.30 + 0.20 = 1.00$.

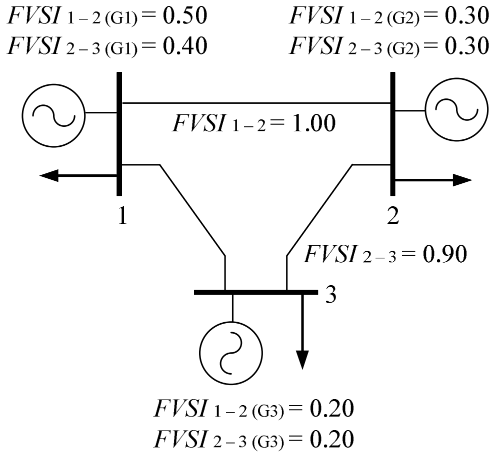

Figure 1: A simple 3-bus power system with traced FVSI values

From these traced *FVSI* values, a ranking list of generator buses can be obtained as tabulated in Table 1. Obviously, generator at bus 1 or G1 is ranked at the top most of the list due to the highest traced *FVSI* value; which is 0.5. This is followed by G2 with 0.3 of traced *FVSI* and lastly G3 with 0.2 of traced *FVSI*. Based on this information, a system operator (SO) has to prioritize G1 for any countermeasures related to generating units, such as generation power dispatch. This is followed by G2 and lastly G3. Thus, the SO is now able to decide intelligently without requiring intuitive decision anymore.

Table 1: Ranking list of generator buses obtained from FVSI-GT

Rank	Generator bus	Contributed in line	Traced *FVSI* ($FVSI_l^{\,k}$)
1	G1	1 – 2	0.5
2	G1	2 – 3	0.4
3	G2	1 – 2 and 2 – 3	0.3
4	G3	1 – 2 and 2 – 3	0.2

3. SIZING ALGORITHM FOR OPTIMAL GENERATION POWER DISPATCH

This section briefly explains the problem formulation and algorithm development using computational intelligence technique for optimal sizing of generator's real and reactive power. The first subsection presents the problem formulation for optimal generation power dispatch, then it is followed with the development of algorithm using the proposed hybrid ant colony algorithm for effective sizing process.

3.1 Problem Formulation

It is important to note that the main purpose of this paper is to validate the reliability of power tracing technique for voltage stability improvement besides transmission service pricing. To be precise, a complex problem formulation of generation power scheduling involving 24 hours operation (as performed by many researchers) is not the main concern. Hence, it is enough to formulate the problem to be static generation power dispatch (run at one-time only). The decision variables, constraints, and objective function to be assigned in the optimization algorithm are as follows.

Decision variable – both real and reactive powers of generators located at PV-bus are treated as the decision variable in the optimization engine. This means that the slack bus generator will not be involved during sizing process and its real and reactive powers are determined using power flow program. All the decision variables are placed in a vector $\mathbf{S}_t$ as in (9); which also represents a *t*-th individual of a population.

$$\mathbf{S_t} = [P_{G1}, P_{G2}, \dots P_{Gk}, \dots P_{G,N_G-1} \cdots$$
$$\dots, Q_{G1}, Q_{G2}, \dots Q_{Gk}, \dots Q_{G,N_G-1}] \qquad (9)$$

Where, P_{Gk} is the generator's real power, Q_{Gk} is the generator's reactive power and N_G is the number of generators.

Constraints – in this paper, the static generation power dispatch is considered in which the simulation is run at one time only [27]. This is totally different with the dynamic power scheduling that requires simulation within 24 hours of operation. Thus, such consideration has reduced the number of constrains to be considered in the optimization engine. For the purpose of simplicity; the real and reactive power limit of generator, bus voltage limit, and power balance as in (10) – (13) being the constraints in the developed algorithm.

$$P_{Gk}^{\min} \le P_{Gk} \le P_{Gk}^{\max} \qquad (10)$$

$$Q_{Gk}^{\min} \le Q_{Gk} \le Q_{Gk}^{\max} \qquad (11)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad (12)$$

$$\sum_{k=1}^{N_G}(P_{Gk} + jQ_{Gk}) = \sum_{i=1}^{N_D}(P_{Di} + jQ_{Di}) + \dots$$
$$\dots + (P_{loss} + jQ_{loss}) \qquad (13)$$

Where, V_i is the voltage at i-th bus, P_{Di} and Q_{Di} are the real and reactive power demand at i-th bus, P_{loss} and Q_{loss} are the total real and reactive power losses, $P_{Gk}^{\min}$ and $P_{Gk}^{\max}$ are the minimum and maximum allowable real power for k-th generator, $Q_{Gk}^{\min}$ and $Q_{Gk}^{\max}$ are the minimum and maximum limit for reactive power of k-th generator, N_G and N_D are the number of generators and loads in the system respectively.

Objective function – Again, the purpose of this paper is to highlight the effectiveness of using power tracing approach over other conventional ranking methods while validating the reliability of power tracing in the field of voltage stability. Hence, only single objective optimization (SOO) problem is considered; which is the maximum *FVSI* of the overall system or $FVSI_{\max}$. However, to provide consistent improvement between the maximum *FVSI* and losses P_{loss}, the following equation was established.

$$\min\{f(P_{Gk}, Q_{Gk}) = FVSI_{\max} + \varepsilon . P_{loss}\} \qquad (14)$$

In (14), the parameter ε is a heuristically defined constant in MW^{-1}. Large value of ε will increase the tendency of the algorithm to highly reduce P_{loss} with low reduction on $FVSI_{\max}$ and vice versa if its value is small.

Generation cost – for simplicity, the cost to be spent for generating real and reactive powers is not included in (14). However, to highlight the advantage of utilizing *FVSI*-GT in terms of economics and voltage stability perspective, the total cost as a result of performing generation power dispatch is considered in the analysis. This means that the generation cost will be calculated only after optimal power dispatch was completed. Based on [28, 29], the total generated real and reactive power cost is represented in (15).

$$C_{PQ} = \underbrace{\sum_{k=1}^{N_G}(a + bP_{Gk} + cP_{Gk}^2)}_{\text{real power cost}} + \dots$$
$$\dots + \underbrace{\sum_{k=1}^{N_G} m_{Gk}Q_{Gk}}_{\text{reactive power cost}} \qquad (15)$$

Where; a, b, and c are the constants for active power cost, m_{Gk} is the generation operational cost coefficient, and C_{PQ} is the total generated real and reactive power cost. As can be seen in (15), there is no scheduling period for 24 hours in determining the generation cost. Since the main objective of this paper is to promote the new application of power tracing, static generation power dispatch which is run at one-time only was considered.

3.2 Algorithm Development

This paper presents a newly developed hybrid algorithm combining both features of Genetic Algorithm (GA) and continuous domain Ant Colony Optimization (ACO_R). For the first time, Socha [30] has developed an ant colony-based optimization algorithm that suits for continuous domain system. By adopting the original working flow of the traditional Ant Colony Optimization (ACO) proposed by [31], the research applied Gaussian normal sampling method during solution update process. This is totally different with the original ACO that applied discrete probability distribution function throughout the whole algorithm. Implementation of ACO$_R$ is rarely performed in many researches as the technique is still new. Nonetheless, due to the fact that the algorithm is suitable for continuous domain problem (like sizing and tuning) and maintains the good property of traditional ACO (such as fast convergence speed), this paper intends to develop an intelligent sizing algorithm using ACO$_R$. Unfortunately, based on heuristic experiment, it was found that sometimes ACO$_R$ failed to achieve optimal solution despite the computation time is small. This phenomenon is called the '*pre-mature*' convergence [32]; in which, the algorithm is trapped into *local optima* region that causes the unwanted solution to be continuously produced even after convergence has been achieved. Hence, to produce a globally optimal solution, the algorithm has to increase its solution variety in order that it can explore the entire solution space during solution update process. To accomplish this, the blended-crossover operation (BLX-α) of GA is adopted; causing the proposed hybrid algorithm to be known as the Blended Crossover Continuous Ant Colony Optimization (BX-CACO). By doing so, each ant in the algorithm will produce their respective '*child*' by firstly selecting the parental solutions, and '*blend*' them together to get the new one. The following step-by-step procedures were developed for optimal sizing of generation power dispatch using BX-CACO.

Step 1: Parameter initialization – at this stage, the essential parameters of BX-CACO such as pheromone evaporation rate, ξ; preference constant, q_0; crossover constant, α; and population size, PS have to be initialized. A load flow program is also run to observe the system condition prior to performing generation power dispatch.

Step 2: Random solution generation – after that, the initial solutions $\mathbf{S_t}$ consist of real and reactive power of generators as in (9) are randomly generated to filled up the Solution Archive-T (SAT); a table introduced by Socha [30] to store the chosen solutions $\mathbf{S_t}$. In SAT, there are '*T*' number of chosen $\mathbf{S_t}$ to be stored. During randomly generated solutions, the decision variables in $\mathbf{S_t}$ have to satisfy the constraints in (10) and (11).

Step 3: Fitness evaluation of randomly generated solution – when SAT is filled with '*T*' number of $\mathbf{S_t}$, the quality of each solution is evaluated by assigning the real and reactive powers from $\mathbf{S_t}$ into tests system data and followed by load flow simulation. The resulted $FVSI_{\max}$ and P_{loss} are used to calculate the fitness in (14). During load flow simulation, the constraints as in (12) and (13) have to be satisfied. Later, all $\mathbf{S_t}$ in SAT are sorted according to their quality with the best one is placed at the topmost of SAT.

Step 4: Solution update process – this is the stage that requires the new solution to be produced. The approach as in traditional ACO is adopted when determining the preference of each ant either to exploit or explore the new solution. It depends on the value of q_0 and q; where, q_0 is a constant specified between 0 and 1 and q is a randomly generated number also in the same range as q_0. If $q < q_0$, the ant prefers exploitation; which means that the top two $\mathbf{S_t}$ from SAT are selected as its parental solutions. Otherwise, the ant goes to exploration by randomly selecting two $\mathbf{S_t}$ from SAT as its parental solutions. Next, the parental solutions are '*blended*' together to produce the new one using the following equations [33, 34].

$$\overline{S_m^c} = \begin{cases} (1-\gamma_m^c).S_{t1}^c + \gamma_m^c.S_{t2}^c \Leftrightarrow S_{t1}^c \leq S_{t2}^c \\ (1-\gamma_m^c).S_{t2}^c + \gamma_m^c.S_{t1}^c \Leftrightarrow S_{t2}^c \leq S_{t1}^c \end{cases} \tag{16}$$

$$\gamma_m^c = (1+2\alpha).u - \alpha \tag{17}$$

$$\sigma_m^c = \xi \sum_{t=1}^{T} \frac{|S_t^c - \overline{S}_m^c|}{T} \tag{18}$$

$$S_{new,m}^c = N(\overline{S}_m^c, \sigma_m^c) \tag{19}$$

Where,

$\overline{S}_m^c$: hybrid mean of *c*-th decision variable for *m*-th ant
S_{t1}^c, S_{t2}^c : selected parents for crossover
γ_m^c : crossover operator
α : crossover constant
u : random number generated within [0, 1]
σ_m^c : standard deviation
S_t^c : other *t*-th solutions in SAT
T : number of $\mathbf{S_t}$ in SAT
ξ : pheromone evaporation rate
$S_{new,m}^c$: the new solution of *c*-th decision variable for *m*-th ant
N : Gaussian normal sampling

In fact, the symbol $\mathbf{S_t}$ and S_t are two different things. $\mathbf{S_t}$ is a vector consists of a group of decision variables (the real and reactive powers of generators); whereas, S_t is one of the decision variables from $\mathbf{S_t}$ (which is a scalar quantity).

Step 5: Fitness evaluation of the new solutions – the evaluation of all newly generated solutions is performed in the same way as in step 3.

Step 6: Update the SAT – the newly generated solutions and the parental solutions in SAT are combined together. If there is *M* number of ants, then the combined population is *T* + *M*. Subsequently, the combined population is sorted based on fitness values and the last *M* solutions from the bottom are discarded to maintain the original size of SAT.

Step 7: Convergence test – if all $\mathbf{S_t}$ in SAT have tolerable fitness difference (i.e. when their fitness is approximately same), the algorithm will be terminated. Otherwise, it will continuously repeat the process from step 4 to step 7.

The overall step-by-step procedures are represented by the flowchart in Figure 2.

4. RESULTS AND DISCUSSION

The developed algorithm for optimal generation power dispatch was tested on IEEE 57-Bus reliability test system (RTS). For the purpose of comparative studies, there are four ranking methods used for selecting the suitable generating units to undergo generation power dispatch. Another approach is also included in the comparison; where, instead of providing a ranking list for generator selection, the approach performs the generation power dispatch involving all generating units. Table 2 summarizes all the ranking methods involved in the comparative studies.

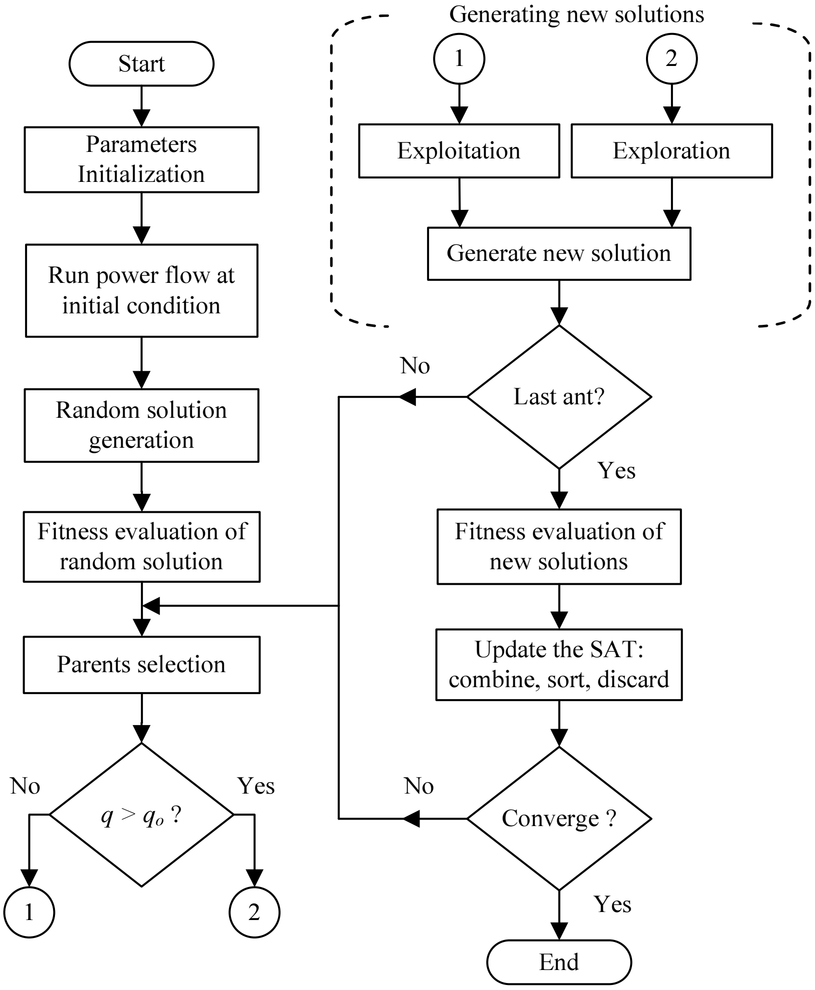

Figure 2: BX-CACO algorithm for optimal generation power dispatch

Table 2: The ranking methods used for selecting suitable generating units

Ranking method	Tracing techniques	Abbreviation
All generators involved	-	AG
FVSI-Generation Tracing	Optimization-based-power tracing proposed in [35]	*FVSI*-GT_A
FVSI-Generation Tracing	Topological Generation Distribution Factor (TGDF) proposed in [17]	*FVSI*-GT_B
Loss Sensitivity	Non-tracing method	LS
Generator Shift Factor Sensitivity	Non-tracing method	GSFS

Note: AG is not a ranking method as it involves all generators in the generation power dispatch

From Table 2, there are two categories of ranking methods excluding AG; i.e. *FVSI*-GT and non-*FVSI*-GT. For *FVSI*-GT, the first one applied optimization-based-power tracing as proposed in [35] and noted as *FVSI*-GT_A; whereas, the second one noted as *FVSI*-GT_B is based on conventional power tracing as proposed by [17]; which is known as the Topological Generation Distribution Factor (TGDF). The remaining conventional ranking methods which are the Loss Sensitivity (LS) and Generator Shift Factor Sensitivity (GSFS) do not require any tracing techniques as they are non-*FVSI*-GT. For all methods in Table 2, the sizing task of generated real and reactive powers was performed using the proposed BX-CACO algorithm as in Figure 2. In the following sections, there are two types of analysis to be discussed. The first subsection analyzes the performance of all ranking methods considering various combinations of generator's ON/OFF-state at maximum loading condition. Later, the second subsection evaluates the performance of all ranking methods under various loading conditions considering only one combination of generator's ON/OFF-state for each loading.

4.1 Determination of the Best Combination of Generator's ON/OFF-state

It is important to note that in IEEE 57-Bus RTS, there are 6 generating units excluding the slack generator; namely the generator at bus 2, 3, 6, 8, 9, and 12 or simply G2, G3, G6, G8, G9, and G12. By performing the proposed *FVSI*-GT, the ranking list of generator buses at maximum loading condition, $Q_{D30,\max}$ = 0.25 p.u. is tabulated in Table 3.

Table 3: Ranking list of generator buses to undergo generation power dispatch at $Q_{D30,max}$ = 0.25 p.u.

Rank	*FVSI*-GT_A	*FVSI*-GT_B	LS	GSFS
1	G12	G12	G12	G6
2	G8	G8	G9	G8
3	G9	G6	G6	G9
4	G6	G9	G3	G3
5	G3	G3	G8	G2
6	G2	G2	G2	G12

The use of the ranking list is as follows. If one generating unit is required for power dispatch; then, G12 has to be firstly selected if *FVSI*-GT_A is used and the other generators are turned off. Similarly, if five generating units are required using *FVSI*-GT_A; then, G12, G8, G9, G6, and G3 are selected in the order of their priority and G2 is turned off. Since there are 6 generating units to undergo generation power dispatch, then 2^6 = 64 combinations of generator's ON/OFF-state are available. The condition prior to optimal generation power dispatch in terms of maximum *FVSI* ($FVSI_{\max}$), minimum voltage magnitude ($V_{\min}$), and losses (P_{loss}) at $Q_{D30,\max}$ = 0.25 p.u. are:

$$\mathbf{FVSI_{max} = 1.221}$$
$$\mathbf{V_{min} = 0.539\ p.u.}$$
$$\mathbf{P_{loss} = 34.237\ MW}$$

After performing optimal generation power dispatch using the proposed BX-CACO, the performance in terms of $FVSI_{\max}$, $V_{\min}$, P_{loss}, and cost to be spent, C_{PQ} are tabulated in Table 4. Despite there are 64 combinations available for generator's ON/OFF-state, only the top 10 with the best performance is given in the table. The symbol

η represents an η-th combination of generator's ON/OFF-state, whereas $N_{G,on}$ is the number of generators involved in generation power dispatch (or the number of turned on generators). Table 4 is organized as follows. The uppermost part gives the performance in terms of $FVSI_{\max}$, $V_{\min}$, P_{loss}, and C_{PQ}; the middle part shows the corresponding combination of generator's ON/OFF-state; and the lowermost part presents the dispatched active and reactive powers after optimal generation power dispatch.

From Table 4, it is obvious that AG (at $\eta = 1$ with $N_{G,on} = 6$) being the best method since all PV-bus generators involved in the power dispatch; with the resulted $FVSI_{\max}$, $V_{\min}$, and P_{loss} are 0.330, 0.971 p.u., and 20.066 MW respectively. This is followed by three ranking methods namely $FVSI$-GT$_A$, $FVSI$-GT$_B$, and LS with only five generators involved in optimal generation power dispatch excluding G2. In terms of performance, the three methods result in comparable voltage stability condition as AG with satisfactory values of $FVSI_{\max}$, $V_{\min}$, and P_{loss}. Based on Table 4, the $FVSI_{\max}$, $V_{\min}$, and P_{loss} resulted from $FVSI$-GT$_A$, $FVSI$-GT$_B$, and LS are 0.351, 0.951 p.u., and 20.392 MW respectively; which are very close to that of AG. Nevertheless, in terms of cost to be spent which is C_{PQ}, there exist large gap between the three ranking methods and AG. Roughly, about \$103,155 – \$92,265 ≈ \$10,000 can be saved using the three ranking methods and this is considered to be significant cost saving with comparable voltage stability improvement as AG.

Table 4: Performance of optimal generation power dispatch for top 10 combinations of generator's ON/OFF-state at $Q_{D30,\,max} = 0.25$ p.u.

η	$N_{G,on}$	Ranking method	$FVSI_{max}$	V_{min} (p.u.)	P_{loss} (MW)	C_{PQ} (\$)
1	6	AG	0.330	0.971	20.066	103,155
2	5	$FVSI$-GT$_A$, $FVSI$-GT$_B$, and LS	0.351	0.951	20.392	92,265
3	4	$FVSI$-GT$_A$, $FVSI$-GT$_B$	0.438	0.842	22.755	90,313
4	5	-	0.440	0.858	24.695	105,583
5	4	LS	0.443	0.848	25.085	99,791
6	5	-	0.451	0.850	25.595	105,483
7	4	-	0.532	0.829	24.882	99,517
8	5	-	0.535	0.815	25.082	101,610
9	4	-	0.543	0.832	26.243	102,188
10	4	-	0.553	0.825	27.955	102,393

			Generator's ON/OFF-state					
η	$N_{G,on}$	Ranking method	G2	G3	G6	G8	G9	G12
1	6	AG	1	1	1	1	1	1
2	5	$FVSI$-GT$_A$, $FVSI$-GT$_B$, and LS	0	1	1	1	1	1
3	4	$FVSI$-GT$_A$, $FVSI$-GT$_B$	0	0	1	1	1	1
4	5	-	1	1	1	0	1	1
5	4	LS	0	1	1	0	1	1
6	5	-	1	1	0	1	1	1
7	4	-	0	1	0	1	1	1
8	5	-	1	0	1	1	1	1
9	4	-	1	0	0	1	1	1
10	4	-	1	0	1	0	1	1

	Dispatched active power (MW)						Dispatched reactive power (MVar)					
η	P_{G2}	P_{G3}	P_{G6}	P_{G8}	P_{G9}	P_{G12}	Q_{G2}	Q_{G3}	Q_{G6}	Q_{G8}	Q_{G9}	Q_{G12}
1	1.65	154.75	127.46	228.29	300.00	300.00	77.97	65.78	0.03	58.66	88.08	89.64
2	-	135.37	128.09	207.90	300.00	300.00	-	85.07	-	59.79	87.73	88.98
3	-	-	175.40	249.99	300.00	300.00	-	-	25.66	65.75	99.46	103.95
4	2.60	180.77	290.69	-	299.99	299.99	78.43	75.99	44.64	-	129.29	88.07
5	-	182.75	289.98	-	300.00	300.00	-	93.57	44.99	-	128.70	91.80
6	1.67	206.64	-	300.00	300.00	300.00	77.89	71.43	-	66.81	87.04	90.71
7	-	207.77	-	299.97	299.99	299.98	-	90.90	-	69.80	84.59	89.10
8	55.09	-	170.05	248.01	300.00	300.00	104.73	-	17.25	65.39	95.40	101.10
9	101.75	-	-	299.99	300.00	300.00	119.32	-	-	108.64	85.08	110.35
10	85.29	-	299.98	-	299.97	300.00	112.38	-	75.09	-	135.24	111.87

Note: logic 1 = generator in ON-state, logic 0 = generator in OFF-state

The next combination of generator's ON/OFF-state is proposed by *FVSI*-GT$_A$ and *FVSI*-GT$_B$ (at $\eta = 3$, $N_{G,on} = 4$) with G2 and G3 were turned off and then followed by LS (at $\eta = 5$, $N_{G,on} = 4$) with G2 and G8 were turned off . The performance of *FVSI*-GT$_A$ and *FVSI*-GT$_B$ in terms of $FVSI_{\max}$, $V_{\min}$, and P_{loss} is slightly worse than that of $\eta = 1$ and $\eta = 2$; but is much better than LS if C_{PQ} is considered. From Table 4, about \$99,791 – \$90,313 ≈ \$9500 can be saved by both *FVSI*-GT methods and this is another significant cost saving with comparable voltage stability improvement as LS.

Lastly, it is found that from the top ten combinations in Table 4, there is no generator's ON/OFF-state proposed by GSFS; entailing that the ranking method failed to give satisfactory voltage stability improvement and cost minimization. Hence, the method is not appropriate to be used for selecting suitable generating units at this condition.

4.2 Optimal Generation Power Dispatch under Various Loading Conditions

After determining the best combination of generator's ON/OFF-state at $Q_{D30,\max} = 0.25$ p.u., it was justified that by turning off only one suitable generating unit, the system performance after optimal generation power dispatch is satisfactory, comparable to that of AG, and has significant cost saving. However, such fact is only true at the maximum loading condition. To validate the reliability, this section discusses how effective each ranking method determines the suitable generating units to undergo generation power dispatch under various loading conditions, Q_{D30}. There are four loading conditions were set during the experiment. After performing the proposed *FVSI*-GT, the ranking list under the four loading conditions is given in Table 5. At each loading condition, the use of the ranking list for selecting any suitable generating units is similar to that of Table 3.

From the analysis in section 4.1, it was validated that for satisfactory voltage stability improvement and significant cost saving; it is enough to turn off only one suitable generating unit with the other five remain turned on. Hence, this section will use the ranking list in Table 5 to select top five generators for optimal generation power dispatch. This implies that any generator listed at rank 6 in the table will be shut down during the experiment. After performing the power dispatch, the results in terms of $FVSI_{\max}$, $V_{\min}$, P_{loss}, and C_{PQ} at four loading conditions are tabulated in Table 6. In the table, the term 'Pre' represents the system condition before the optimal generation power dispatch. Using the results from Table 6, the graphical illustrations of $FVSI_{\max}$, $V_{\min}$, P_{loss}, and C_{PQ} are plotted and depicted in Figure 3 to Figure 6 respectively.

Table 5: Ranking list of generator buses under four loading conditions

Q_{D30} (p.u.)	Rank	*FVSI*-GT$_A$	*FVSI*-GT$_B$	LS	GSFS
0.02	1	G12	-	G12	G12
	2	G9	-	G6	G6
	3	G3	-	G3	G9
	4	G8	-	G8	G3
	5	G6	-	G2	G8
	6	G2	-	G9	G2
0.09	1	G12	G12	G12	G6
	2	G9	G8	G6	G8
	3	G8	G3	G3	G9
	4	G6	G6	G8	G3
	5	G3	G9	G2	G2
	6	G2	G2	G9	G12
0.17	1	G12	G12	G9	G6
	2	G6	G8	G6	G9
	3	G9	G6	G3	G8
	4	G8	G9	G8	G3
	5	G3	G3	G2	G2
	6	G2	G2	G12	G12
0.25	1	G12	G12	G12	G6
	2	G8	G8	G9	G8
	3	G9	G6	G6	G9
	4	G6	G9	G3	G3
	5	G3	G3	G8	G2
	6	G2	G2	G2	G12

From Figure 3, it is observed that the optimal reduction of $FVSI_{\max}$ is resulted from AG as the line trend is consistent throughout the loading conditions. This is followed by LS, *FVSI*-GT$_A$ and *FVSI*-GT$_B$ with also consistent trend of improvement. Despite AG is the best approach, the quality of $FVSI_{\max}$ after generation power dispatch is comparable to that of *FVSI*-GT$_A$ and *FVSI*-GT$_B$. Based on Table 6; at $Q_{D30} = 0.17$ p.u., the value of $FVSI_{\max}$ improved by AG and both *FVSI*-GT methods are 0.305 and 0.346 respectively; which is still satisfactory. The trend resulted from GSFS is not reliable as the improved $FVSI_{\max}$ at $Q_{D30} = 0.25$ p.u. is still hazardous to the system, i.e. 0.631.

Later, the improvement trend of $V_{\min}$ is depicted in Figure 4. As the improved $FVSI_{\max}$ by AG is consistent, the improved $V_{\min}$ is still satisfactory at all loading conditions. This is followed by *FVSI*-GT$_A$ and *FVSI*-GT$_B$ with consistent magnitude of improved $V_{\min}$. From Table 6, the improved $V_{\min}$ by *FVSI*-GT$_A$ at all loading conditions is above than 0.95 p.u.; which is at safe level. The LS has a slight difference of $V_{\min}$ trend at $Q_{D30} = 0.17$ p.u. with the improved voltage magnitude of 0.92 p.u., while

Table 6: Performance of optimal generation power dispatch under various loading conditions

Q_{D30} (p.u.)	Method	Generator ON/OFF-state						$FVSI_{max}$	V_{min} (p.u.)	P_{loss} (MW)	C_{PQ} ($)
		G2	G3	G6	G8	G9	G12				
0.02	Pre	-	-	-	-	-	-	0.149	0.871	26.479	-
	AG	1	1	1	1	1	1	0.116	0.995	12.163	80,149
	FVSI-GT$_A$ GSFS	0	1	1	1	1	1	0.119	0.964	13.245	72,162
	LS	1	1	1	1	0	1	0.118	0.970	20.178	78,699
	FVSI-GT$_B$	-	-	-	-	-	-	-	-	-	-
0.09	Pre	-	-	-	-	-	-	0.468	0.809	27.156	-
	AG	1	1	1	1	1	1	0.173	0.999	12.901	85,050
	FVSI-GT$_A$ *FVSI*-GT$_B$	0	1	1	1	1	1	0.184	0.966	13.131	79,174
	LS	1	1	1	1	0	1	0.179	0.957	20.801	82,242
	GSFS	1	1	1	1	1	0	0.175	0.952	37.644	87,630
0.17	Pre	-	-	-	-	-	-	0.803	0.725	28.929	-
	AG	1	1	1	1	1	1	0.305	0.985	15.355	93,016
	FVSI-GT$_A$ *FVSI*-GT$_B$	0	1	1	1	1	1	0.346	0.954	15.647	86,371
	LS GSFS	1	1	1	1	1	0	0.304	0.920	40.116	95,325
0.25	Pre	-	-	-	-	-	-	1.221	0.539	34.237	-
	AG	1	1	1	1	1	1	0.330	0.971	20.066	103,155
	FVSI-GT$_A$ *FVSI*-GT$_B$ LS	0	1	1	1	1	1	0.351	0.951	20.392	92,265
	GSFS	1	1	1	1	1	0	0.631	0.794	44.459	104,324

Note: logic 1 = generator in ON-state, logic 0 = generator in OFF-state

GSFS failed to provide satisfactory $V_{\min}$ at Q_{D30} = 0.25 p.u. with the improved voltage magnitude of only 0.794 p.u.

Subsequently, the improvement trend of P_{loss} is depicted in Figure 5. It is observed that both *FVSI*-GT methods result in consistent trend as AG throughout the loading conditions. However, the conventional ranking methods which are LS and GSFS have unreliable improvement trend as the improved P_{loss} at certain loading conditions is higher than that of Pre condition. For instance, LS results in higher P_{loss} than Pre condition at Q_{D30} = 0.17 p.u.; while GSFS at Q_{D30} = 0.09 p.u. to Q_{D30} = 0.25 p.u. This implies that both conventional ranking methods failed to establish acceptable voltage stability improvement.

The last analysis is on C_{PQ}, as illustrated in Figure 6. It is undeniable that for this time, the most economical approaches are the proposed *FVSI*-GT$_A$ and *FVSI*-GT$_B$. By subtracting C_{PQ} of *FVSI*-GT$_A$ from C_{PQ} of AG, the cost saving provided by the proposed method is as follows; at Q_{D30} = 0.02 p.u., cost saving ≈ $8,000; at Q_{D30} = 0.09 p.u., cost saving ≈ $5,900; at Q_{D30} = 0.17 p.u., cost saving ≈ $6,600; and at Q_{D30} = 0.25 p.u., cost saving ≈ $10,900. This is considerably large cost saving promoted by *FVSI*-GT methods with comparable and consistent improvement on $FVSI_{\max}$, $V_{\min}$, and P_{loss}. On the other hand, the conventional ranking methods are not successful for establishing an economical scheme of generation power dispatch. At Q_{D30} = 0.17 p.u., LS required higher C_{PQ} than AG with a cost waste of $2,300; whereas, GSFS results in cost wastes from Q_{D30} = 0.09 p.u. to Q_{D30} = 0.25 p.u.

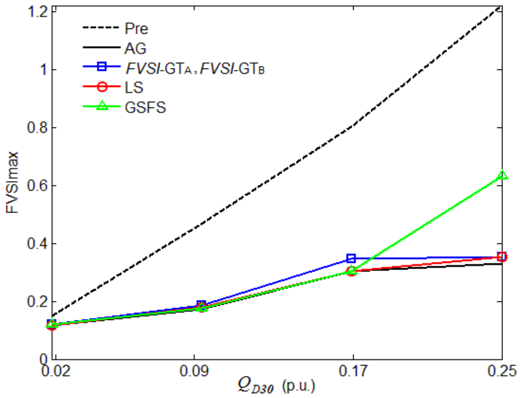

Figure 3: Variation of $FVSI_{max}$ with respect to reactive loading, Q_{D30}

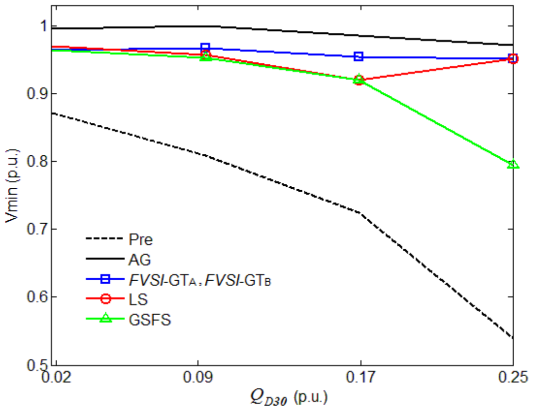

Figure 4: Variation of V_{min} with respect to reactive loading, Q_{D30}

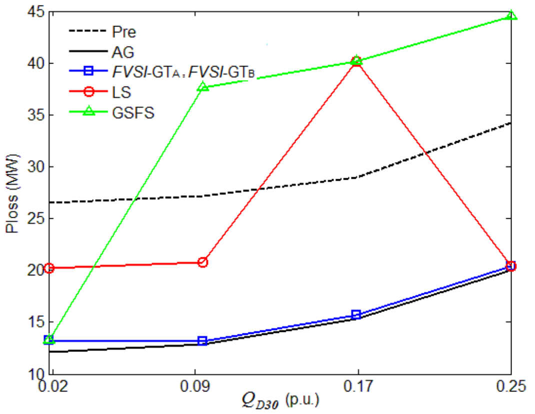

Figure 5: Variation of P_{loss} with respect to reactive loading, Q_{D30}

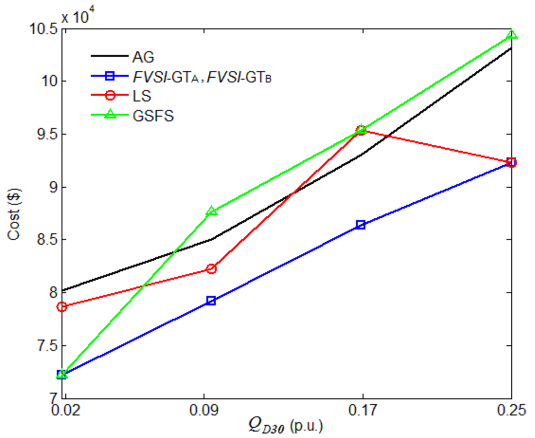

Figure 6: Variation of cost with respect to reactive loading, Q_{D30}

From the analysis of this section, it is justified that for an economical and optimal generation power dispatch, the most consistent method is *FVSI*-GT$_A$. Regardless of loading conditions, the method results in satisfactory voltage stability improvement with low cost to be spent concurrently. Despite *FVSI*-GT$_B$ was able to give same performance as *FVSI*-GT$_A$, it is only for second, third, and fourth loading condition. By referring to Table 5 at the first loading condition; i.e. Q_{D30} = 0.02 p.u., *FVSI*-GT$_B$ has no ranking list and therefore there is no improvement results at this condition. Since *FVSI*-GT$_B$ utilized TGDF as the tracing method, the matrix to be inversed was singular; thus, no tracing results can be produced. This is the weakness of TGDF as the tracing process is only workable at certain loading conditions. Next, the conventional ranking methods (LS and GSFS) provide inconsistent voltage stability improvement with considerably large cost wastes, while AG failed to establish economical generation power dispatch with large cost to be spent as compared to *FVSI*-GT$_A$.

4.3 Effectiveness of BX-CACO as an Optimizer

This section analyzes the effectiveness of BX-CACO in performing the optimization process. Other competing AI algorithms are the original continuous domain Ant Colony Optimization (ACO$_R$), Evolutionary Programming (EP), and Genetic Algorithm (GA). The validation takes place on three test systems; namely, the IEEE 14-Bus, 30-Bus, and 57-Bus RTS. For all test systems, only one suitable generating unit was turned off using the ranking list of *FVSI*-GT$_A$. The results are tabulated in Table 7.

Firstly, in terms of the improved $FVSI_{max}$ and P_{loss}; the proposed BX-CACO results in comparable improvement as EP for all test systems. For example, in 57-bus system the improved $FVSI_{max}$ by BX-CACO and EP are 0.3510 and 0.3475 respectively; which is very close. However, the difference of the required computation time by both algorithms is significantly large. In all test systems, BX-CACO is able to finish the optimization process much faster than EP. For instance, in 57-Bus system only 162 seconds are required by the proposed algorithm; which is equivalent to 24 minutes earlier than EP. Small number of population size (PS) required by BX-CACO becomes the main reason for the fast computation time. As compared to EP that requires PS = 50, the proposed algorithm can perform the optimization with PS = 5 only.

Table 7: Comparison of various AI algorithms at maximum loading condition – 1 generator was turned off using FVSI-GT$_A$ with ε = 100

Systems	Algorithm	$FVSI_{\max}$	P_{loss} (MW)	t_c (sec)	PS
14-Bus	Pre	1.0231	31.4512	-	-
	BX-CACO	0.1501	9.0125	34	5
	ACO_R	0.1498	12.7762	37	5
	EP	0.1503	8.9914	390	50
	GA	0.1581	9.1516	410	50
30-Bus	Pre	0.9984	39.7134	-	-
	BX-CACO	0.2927	10.0012	65	5
	ACO_R	0.2897	9.9889	64	5
	EP	0.3011	9.9957	780	50
	GA	0.3104	10.3085	790	50
57-Bus	Pre	1.2210	34.2370	-	-
	BX-CACO	0.3510	20.3920	162	5
	ACO_R	0.6986	29.5814	158	5
	EP	0.3475	19.8796	1630	50
	GA	0.3711	21.1011	2450	50

Note: t_c and PS stand for computation time and population size respectively.

Next, the original ACO_R results in comparable performance with fast computation time as BX-CACO. Nevertheless, this is no longer true if 57-Bus system is considered. From Table 7, the improved $FVSI_{\max}$ and P_{loss} in 57-Bus system are 0.6986 and 29.5814 MW; which is still unsatisfactory. The problem known to be '*pre-mature convergence*' becomes the main reason for such failure. The original ACO_R has less solution variety that causes it to be trapped into *local optim*a region. To solve this, the proposed BX-CACO adopted the blended-crossover operator of GA with the aim of producing wide solution variety. Such hybridization has made BX-CACO to be able escaping from *local optima* region and thus producing a *global optima* solution. Lastly, GA is the only algorithm that lack of any advantages as compared to others. The algorithm results in fair improvement (but not the best) with considerably large computation time, especially in 57-Bus system.

5. CONCLUSION

In conclusion, it was justified that besides solving non-discriminatory issues in deregulated power market, power tracing technique is practical for alternative application; which is voltage stability improvement. In this paper, a new technique for selecting suitable generating units to undergo static generation power dispatch has been proposed; namely the *FVSI*-GT. By applying power tracing approach, the technique traces the value of *FVSI* contributed by individual generator. Subsequently, a ranking list of generator buses is derived using the traced *FVSI* values and from that, the most suitable generating units committed for power dispatch can be determined precisely. Contrary to other conventional ranking methods, the ranking list obtained from *FVSI*-GT is reliable and valid at all loading conditions. To be precise, the selected generators for generation power dispatch using *FVSI*-GT has resulted in consistent and satisfactory voltage stability improvement regardless of system condition. In addition, the total cost to be spent using *FVSI*-GT is more economical as compared to the conventional methods despite no multi-objective optimization (MOO) was implemented. Lastly, a new hybrid algorithm known as BX-CACO has been developed and it was revealed that the proposed algorithm is suitable for fast optimization process with better quality of improvement concurrently.

ACKNOWLEDGEMENT

The authors would like to acknowledge The Research Management Institute (RMI) UiTM, Shah Alam and Ministry of Higher Education Malaysia (MOHE) for the financial support of this research. This research is supported by MOHE under the Fundamental Research Grant Scheme (FRGS) with project code: (File No : 600-RMI/FRGS 5/3 (84/2013).

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