A New Technique for FACTS Devices Placement via Stability Index-Load Tracing

Z. Hamid, I. Musirin, M. M. Othman, M. N. A. Rahim

Abstract— **Placement of shunt elements such as FACTS devices can be performed through various methods such as sensitivity analysis, optimization method, and the method that is rarely applied, termed as power tracing. Currently, the usage of power tracing technique is majorly limited to the field of transmission service pricing although there are various methods that have been developed by researchers. Because of that, this paper promotes a new technique for identifying the most suitable load bus to be selected for shunt element placement by means of Fast Voltage Stability Index Load Tracing (*FVSI*-LT) via a new hybrid algorithm, Blended Crossover Continuous Ant Colony Optimization (BX-CACO). Validation on IEEE 14 and 57-Bus RTS revealed that the proposed method has capability to be applied into real system.**

Index Terms—**BX-CACO, FACTS, *FVSI*-LT, Placement method**

I. Introduction

THERE are various methods available for selecting the best location for shunt element placement at consumer site. The method can be sensitivity analysis [1], [2], stability index based analysis [3], [4], optimization technique [5], [6], and lastly the method that is rarely applied by many researchers, which is termed as power tracing technique. Currently, power tracing approach is only limited to the field of power system economics where allocation of losses and transmission service charge are determined by tracing the power contribution and extraction factors of generators and loads respectively through various methods. Article [7] and [8] are considered as the pioneered method for tracing the flow of electricity. This method proposed Topological Generator and Load Distribution Factor (TGLDF) technique to trace the power contributed by individual generator and load by treating the system to be lossless. A method based on bus impedance matrix for tracing the complex power among generators has been proposed by [9] in which the algorithm started by tracing the contribution of generators on bus voltages and line currents, and subsequently multiplied both of the traced voltages and currents to obtain the traced complex powers. Unfortunately, the method is unable to provide full positive sharing among the participated generators. Article [10] proposes losses allocation via Genetic Algorithm (GA) with simple formulation steps. This is considered as the first research that applied Artificial Intelligence (AI) for tracing the electricity of power system. Other research regarding on power tracing technique can be explored via [11] – [13]. Nevertheless, all of the power tracing methods discussed before is only limited to the field of transmission service pricing, that is to say they lack of considering the application of the developed method into voltage stability field, for instance in shunt element placement problem (such as capacitor bank and shunt FACTS devices).

There are many ways for installing FACTS devices with optimal performance in terms of cost and system stability. Reference [14] has implemented maximum loadability identification technique for obtaining the most suitable location for placement of unified power flow controller (UPFC) in power system. The method is performed by increasing gradually the load reactive power on each bus and calculating the stability index resulted from the increment. Another research that concerned about installation technique of FACTS devices has also

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been conducted by [15], where STATCOM has been chosen as a tool for improving power system optimal level, the research used Particle Swarm Optimization (PSO) and Continuation Power Flow (CPF) for improving voltage profile, system losses and maximizing system loadability. A sensitivity analysis based FACTS device placement for improving static and transient stability has been explored by [16] where in obtaining the finest location of installation, the research used a sensitivity index based on voltage and reactive power for selecting the suitable buses.

This paper proposes a power tracing based selection method for selecting the most suitable load bus for shunt element placement considering congestion level and voltage stability. The newness in this paper is that instead of using the magnitude of power flow on a line as what the previous research did, the proposed method uses stability index based tracing technique to identify which of the load buses in the system that causes the highest congestion level on a particular line. The stability index to be traced is called Fast Voltage Stability Index (*FVSI*) by means of a new hybrid algorithm, Blended Crossover Continuous Ant Colony Optimization (BX-CACO) technique.

II. Development of *FVSI*-Load Tracing (*FVSI*-LT)

I. Musirin [17] has developed a line based stability index to indicate the stability of transmission lines, which is termed as Fast Voltage Stability Index (*FVSI*). As a matter of fact, *FVSI* was inspired by other line based indices such as Line Stability Factor (*LQP*) and Line Stability Index (L_{mn}) but the newness in *FVSI* is that it has been derived from quadratic equation and also easy to be utilized as the report in [17], [18] has proven that the index is suitable to be used in voltage collapse prediction, maximum loadability identification and voltage stability assessment. The *FVSI* of an l-th line can be represented in (1).

$$FVSI_l = \frac{4Z_l^2 Q_r}{V_s^2 X_l} \tag{1}$$

Where Z_l, X_l, Q_r, and V_i are the line impedance, line reactance, receiving end power, and sending end voltage respectively. It is important to note that for a stable power system, the *FVSI* should be less than unity. The purpose of tracing the stability index *FVSI* contributed by individual load is to know who being the major contributor for a congested or stressed transmission line. By doing so, a system operator (SO) can determine which of the load buses is the most suitable bus to be performed any corrective and preventive actions considering voltage stability improvement. The derivation of the modified *FVSI* equation of l-th line in (1) for the purpose of *FVSI*-LT is given below.

$$FVSI_l = FVSI_l^1 + FVSI_l^2 + \ldots + FVSI_l^{i,nload} \tag{2}$$

$$FVSI_l = \frac{4Z_l^2 Q_r^1}{V_s^2 X_l} + \frac{4Z_l^2 Q_r^2}{V_s^2 X_l} + \ldots + \frac{4Z_l^2 Q_r^{i,nload}}{V_s^2 X_l} \tag{3}$$

$$FVSI_l = \frac{4Z_l^2}{V_s^2 X_l}\left(Q_r^1 + Q_r^2 + \ldots + Q_r^{i,nload}\right) \tag{4}$$

$$\therefore FVSI_l = \frac{4Z_l^2}{V_s^2 X_l}\sum_{i=1}^{nload} Q_r^i = \frac{4Z_l^2}{V_s^2 X_l}\sum_{i=1}^{nload} x_r^i . Q_{Li} \tag{5}$$

Where *nload*, Q_r^i, and x_r^i are the number of loads, the receiving end power and fraction extracted by i-th load respectively. From (5), it is revealed that the *FVSI* of l-th line contributed by i-th load of power Q_{Li} can be mathematically represented as in (6).

$$FVSI_l^i = \frac{4Z_l^2}{V_s^2 X_l}\left(x_r^i . Q_{Li}\right) \tag{6}$$

By tracing the fraction x_r^i for all loads, the priority ranking of load buses for the purpose of shunt element installation can be realized by means of calculating the traced $FVSI_l^i$ via (6).

III. The Blended Crossover Continuous Ant Colony Optimization (BX-CACO)

This section presents a novel optimization innovation which is inspired by the blended-alpha crossover operation of Genetic Algorithm (GA) and fast convergence property of continuous domain Ant Colony Optimization (ACO_R). The proposed algorithm is exactly similar to the original algorithm of ACO_R, as proposed by Socha and Dorigo [19] except for the way how to calculate the mean and standard deviation in solution updating process. The newness introduced in the previous ACO$_R$ is about the hybrid mean, which is generated via blended crossover operator (BLX-α) of GA. After conducting a solemn research regarding on the hybridization method, the hybrid mean and the corresponding standard deviation can be calculated via (7) and (9) respectively

$$\overline{S_m^c} = \begin{cases} (1-\gamma_m^c).S_{t1}^c + \gamma_m^c.S_{t2}^c & \Leftrightarrow \quad S_{t1}^c \le S_{t2}^c \\ (1-\gamma_m^c).S_{t2}^c + \gamma_m^c.S_{t1}^c & \Leftrightarrow \quad S_{t2}^c \le S_{t1}^c \end{cases} \tag{7}$$

$$\gamma_m^c = (1+2\alpha).u - \alpha \tag{8}$$

$$\sigma_m^c = \zeta \sum_{t=1}^{T} \frac{|S_t^c - \overline{S}_m^c|}{T} \tag{9}$$

where

$\overline{S}_m^c, \sigma_m^c$	:	hybrid mean & standard deviation of c-th control variable for m-th ant respectively.
S_{t1}^c, S_{t2}^c	:	t-th parent solutions for c-th control variable.
S_t^c	:	t-th solution of c-th control variable.
γ_m^c, α and u	:	Crossover operator, crossover constant, and random number in [0,1] respectively.
ξ	:	pheromone evaporation rate.
T	:	size of *Solution Archive T.*

It is essential to tell that after completing their tour (after updating all control variables), each ant will store their updated solution in *Solution Archive T*, a table where the solutions are sorted according to quality of fitness. Equation (10) represents the sampling method for updating the current solution by an ant.

$$S_{new,m}^c = N(\overline{S}_m^c, \sigma_m^c) \tag{10}$$

where

$S_{new,m}^c$	:	new solution of c-th ontrol variable for m-th ant.
N	:	Gaussian normal sampling with hybrid mean $\overline{S}_m^c$ and standard deviation σ_m^c.

IV. FORMULATION TECHNIQUE

Prior to performing the developed *FVSI*-LT technique, it is important to find the finest way in formulating the optimization components (i.e. the control variables, constraints, and objective function) into the case study. The best way to formulate the BX-CACO into *FVSI*-LT problem is presented below.

i) Control Variables

The control variables in the context of *FVSI*-LT are represented by the receiving end fraction x_r^i and generator power fraction x_{gk}^i extracted by loads in the system. For simplicity, all of the fractions are placed in a matrix **X**, which also represents a BX-CACO's t-th solution in *Archive-T*. This implies that if the developed BX-CACO engine requires archive's size of fifty, then the optimization engine consists of fifty matrices **X**. The size of matrix **X** is (nbr + $ngen$) x $nload$ and the terms nbr and $ngen$ stand for the number of transmission lines and generators. A t-th matrix **X** is given as follow.

$$\mathrm{X} = \begin{bmatrix} x_{r1}^1 & \cdots & x_{r1}^i & \cdots & x_{r1}^{nload} \\ x_{r2}^1 & & x_{r2}^i & & x_{r2}^{nload} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{rl}^1 & & x_{rl}^i & & x_{rl}^{nload} \\ \vdots & & \vdots & & \vdots \\ x_{r,nbr}^1 & \cdots & x_{r,nbr}^i & \cdots & x_{r,nbr}^{nload} \\ x_{g1}^1 & & x_{g1}^i & & x_{g1}^{nload} \\ x_{g2}^1 & & x_{g2}^i & & x_{g2}^{nload} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{gk}^1 & & x_{gk}^i & & x_{gk}^{nload} \\ \vdots & & \vdots & & \vdots \\ x_{g,ngen}^1 & \cdots & x_{g,ngen}^i & \cdots & x_{g,ngen}^{nload} \end{bmatrix} \tag{11}$$

ii) Constraints

The well known equality and non-equality constraints according to [12] that should be specified in the developed BX-CACO engine are as follows.

$$Q_r = \sum_{i=1}^{nload} x_r^i.Q_{Li} \tag{12}$$

$$Q_{gk} = \sum_{i=1}^{nload} x_{gk}^{i} . Q_{Li} \tag{13}$$

$$x_r^i , x_{gk}^i \geq 0 \tag{14}$$

iii) Objective Function

A hypothetical equation has been derived to be utilized as the fitness for guiding the BX-CACO algorithm in searching mechanism. The objective function for *FVSI*-LT has been derived from the individual power balance equation of load, as in (15). After several derivation and simplification, the objective functions to be utilized in BX-CACO engine for *FVSI*-LT is represented by (16). The variable x_{loss} in (16) represents the fraction of losses on a particular line contributed by the system's loads.

$$Q_{Li} = \sum_{k=1}^{ngen} Q_{gk}^{i} - \sum_{l=1}^{nbr} Q_{loss,\,l}^{i} \tag{15}$$

$$E_{Li}(x) = \sum_{k=1}^{ngen} x_{gk}^{i} - \sum_{l=1}^{nbr} x_{loss,\,l}^{i} - 1 \tag{16}$$

In the above equations, the error $E_{Li}(x)$ will be minimized as low as possible by BX-CACO search engine until its value approaches zero. After determining the best way to formulate the BX-CACO parameters and components into *FVSI*-LT problem, the complete algorithm has been developed before implementing into source code, as illustrated in Fig. 1.

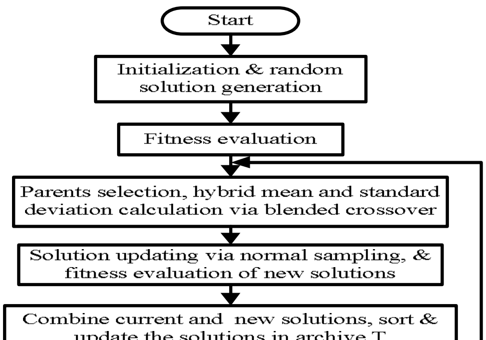

Fig. 1: Full algorithm of BX-CACO

V. Results and Discussion

The developed BX-CACO search engine has been implemented via MATLAB software and validated on IEEE 14 and 57 bus reliability test system (RTS). For ensuring the feasibility of the proposed algorithm, comparison with other method has also been conducted, in this case the Topological Load Distribution Factor (TLDF) which is proposed by [7], [8] and other non-*FVSI*-LT method which is Loss Sensitivity (LS) technique.

The traced *FVSI* contributed by loads for 14-bus system are tabulated in Table 1 and Table II for BX-CACO and TLDF method respectively. By inspection, there is much difference in terms of the total *FVSI* on certain transmission lines for both methods, for instance, line ℓ3, ℓ4, and ℓ5. The reason is because the BX-CACO based *FVSI*-LT performs actual value based tracing process (without treating the power system as the lossless system), whereas the TLDF based method applies the concept of '*net flows*', which implies that the losses on each line have been subtracted from the individual generator's power so as to provide a lossless power system. On account of that, the receiving end power flow to be used for traced *FVSI* calculation is also different from the BX-CACO.

The load buses priority ranking for 14-bus system is tabulated in Table III. By inspection, it can be interpreted that the load at bus number 1 is the most suitable location for any corrective and preventive actions required by the SO. Action like shunt element installation (such as capacitor bank or static Var compensator (SVC)) for the purpose of providing reactive power support should be performed at bus 1 as the load at this bus causes the major effect on line *FVSI* (ℓ14 for BX-CACO and ℓ1 for TLDF). To be more precise, load at bus 1 being the major contributor for the high congestion level of the system. The best location after bus 1 for shunt element installation should be bus 2 and bus9 for BX-CACO and TLDF method respectively.

TABLE 1
FVSI-LT RESULTS FOR 14-BUS SYSTEM VIA BX-CACO

Line	Load Buses									
Number	1	2	8	9	10	11	12	13	14	Total
$\ell 1$	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.110
$\ell 2$	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027
$\ell 3$	0.056	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.059
$\ell 4$	0.040	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
$\ell 5$	0.027	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033
$\ell 6$	0.033	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.037
$\ell 7$	0.007	0.010	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.024
$\ell 8$	0.107	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.109
$\ell 9$	0.016	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.018
$\ell 10$	0.060	0.064	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.147
$\ell 11$	0.055	0.003	0.004	0.007	0.002	0.001	0.000	0.000	0.002	0.075
$\ell 12$	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.025	0.002	0.028
$\ell 13$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.036	0.055
$\ell 14$	0.125	0.083	0.003	0.007	0.000	0.000	0.000	0.000	0.001	0.219
$\ell 15$	0.069	0.005	0.000	0.003	0.000	0.000	0.000	0.000	0.004	0.082
$\ell 16$	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
$\ell 17$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004
$\ell 18$	0.005	0.002	0.002	0.006	0.010	0.000	0.000	0.000	0.030	0.056
$\ell 19$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.005	0.031
$\ell 20$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080

TABLE II
FVSI-LT RESULTS FOR 14-BUS SYSTEM VIA TLDF

Line	Load Buses									
Number	1	2	8	9	10	11	12	13	14	Total
$\ell 1$	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.110
$\ell 2$	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027
$\ell 3$	0.035	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.046
$\ell 4$	0.032	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042
$\ell 5$	0.020	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
$\ell 6$	0.008	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.011
$\ell 7$	0.004	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.006
$\ell 8$	0.024	0.006	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.033
$\ell 9$	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005
$\ell 10$	0.024	0.003	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.034
$\ell 11$	0.000	0.000	0.000	0.003	0.053	0.017	0.000	0.000	0.000	0.073
$\ell 12$	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.009	0.028
$\ell 13$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.024	0.054
$\ell 14$	0.019	0.005	0.002	0.098	0.000	0.000	0.000	0.000	0.002	0.126
$\ell 15$	0.001	0.000	0.000	0.069	0.000	0.000	0.000	0.000	0.001	0.072
$\ell 16$	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
$\ell 17$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004

It is important to tell that although the most suitable load bus can also be determined without *FVSI*-LT (i.e. by simply calculating the *FVSI* via (1) for all lines), the results might be inaccurate. For instance in the last column of Table 1 and Table II, the line that has the highest *FVSI* for both methods is line $\ell 14$, which is located between bus 5 and 7. Without tracing technique, the SO might choose either bus 5 or 7 to be performed any corrective and preventive actions. However, the results provided by tracing method show that among the top priority ranking in Table

III, no bus 5 or 7 is listed. This means that those buses are not categorized as the major contributor of *FVSI* on any lines in the system. The similar explanation for Table IV, which tabulates the load buses priority ranking results for 57-bus system, is also applicable.

It is for BX-CACO and TLDF method respectively. It is important to tell that although the most suitable load bus can also be determined without *FVSI*-LT (i.e. by simply calculating the *FVSI* via (1) for all lines), the results might be inaccurate. For instance in the last column of Table 1 and Table II, the line that has the highest *FVSI* for both methods is line ℓ14, which is located between bus 5 and 7. Without tracing technique, the SO might choose either bus 5 or 7 to be performed any corrective and priority ranking in Table III, no bus 5 or 7 is listed. This means that those buses are not categorized as the major contributor of *FVSI* on any lines in the system.

TABLE III
LOAD BUSES PRIORITY RANKING FOR 14-BUS SYSTEM

BX-CACO					TLDF					LS
Load bus	Line numbe r	From	To	*FVSI*-LT	Load bus	Line number	From	To	*FVSI*-LT	Load Bus
1	ℓ14	5	7	0.1248	1	ℓ1	2	1	0.1101	12
2	ℓ14	5	7	0.0835	9	ℓ14	5	7	0.0983	14
14	ℓ20	13	14	0.0796	14	ℓ20	13	14	0.0796	11
13	ℓ19	12	13	0.0258	10	ℓ11	4	11	0.0534	3
8	ℓ10	4	8	0.0233	13	ℓ13	4	13	0.0299	13
10	ℓ18	11	10	0.0096	11	ℓ11	4	11	0.0166	4
9	ℓ14	5	7	0.0067	2	ℓ3	3	2	0.0105	10
11	ℓ11	4	11	0.0014	8	ℓ10	4	8	0.0071	6
12	ℓ12	4	12	0.0008	12	ℓ12	4	12	0.0071	8

Note: BX-CACO and TLDF are *FVSI*-LT method, whereas LS is non-*FVSI*-LT method

TABLE IV
LOAD BUSES PRIORITY RANKING FOR 57-BUS SYSTEM

BX-CACO					TLDF					LS
Load Bus	Line numbe r	From	To	*FSI*-LT	Load Bus	Line numbe r	From	To	*FVSI*-LT	Load Bus
31	ℓ41	30	31	0.1061	31	ℓ41	30	31	0.1061	9
57	ℓ74	39	57	0.1011	57	ℓ74	39	57	0.1010	5
50	ℓ62	51	50	0.0984	50	ℓ62	51	50	0.0984	1
32	ℓ44	34	32	0.0964	33	ℓ44	34	32	0.0908	3
42	ℓ52	11	41	0.0562	42	ℓ53	41	42	0.0844	6
38	ℓ64	13	49	0.0541	49	ℓ64	13	49	0.0626	8
30	ℓ40	25	30	0.0535	9	ℓ11	12	9	0.0565	12
2	ℓ1	1	2	0.0470	56	ℓ72	41	56	0.0508	2
54	ℓ68	55	54	0.0426	2	ℓ1	1	2	0.0471	55
53	ℓ67	54	53	0.0425	53	ℓ67	54	53	0.0425	51

Note: BX-CACO and TLDF are *FVSI*-LT method,

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The similar explanation for Table IV, which tabulates the load buses priority ranking results for 57-bus system, is also applicable. As can be seen, the non-*FVSI*-LT method, which is LS results to totally different priority ranking for load buses as compared to BX-CACO and TLDF method for both test systems. This implies that LS is unable to provide reliable signal for an SO when confronting with problems related to voltage stability assessment and improvement.

VI. Conclusion

This paper has presented a new technique for identifyingthe most suitable load buses for the purpose of preventiveand corrective actions by means of *FVSI*-LT. The methodhas promoted a reliable technique for ranking the priorityof load buses for shunt element installation accurately. Thiscan be valuable knowledge for a system operator (SO) whenconfronting with a problem related to voltage stabilityassessment and improvement. The SO can decideintelligently for any actions based on the informationprovided by the *FVSI*-LT results, which means that theoperator's intuitive decision is no longer needed. Moreover,the Artificial Intelligence (AI) based *FVSI*-LT via the newhybrid algorithm, Blended Crossover Continuous AntColony Optimization (BX-CACO) has also been promoted in this paper and the results using the developed BX-CACOalgorithm is comparable to the alternative technique suchas Topological Load Distribution Factor (TLDF) method.

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