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BUS PRIORITY RANKING VIA STABILITY INDEX TRACING AND EVOLUTIONARY PROGRAMMING

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ABSTRACT

There are various methods applied for indicating the most sensitive bus for any corrective and preventive actions like power scheduling at generation site and shunt element placement such as capacitor bank and FACTS devices at load site. The methods can be sensitivity analysis, optimization method, stability index based ranking and lastly 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. By virtue of that, this paper promotes a new technique for identifying the most suitable generator bus to be performed power scheduling and the best load bus for shunt element installation by means of Fast Voltage Stability Index Tracing (*FVSI*-T) via Evolutionary Programming (EP). Validation on IEEE 14-Bus and 57-Bus reliability test system (RTS) revealed that the proposed method has great capability to be applied into real system.

Keywords: *EP, FVSI-T, Power Scheduling, Shunt Element Placement*

1. INTRODUCTION

The well known ancillary services for a power system are long-term power reserves, power, frequency, voltage, and reactive power control [1]. However, the most significant ancillary service is reactive power control and management as it has major implication on system performance in terms of stability, security, reliability, and economy, especially for a deregulated environment [2]. In fact, to have a power system within secure operating condition and less congestion on transmission lines, a transmission service provider (TRANSCO) should well control the flow of reactive power from one bus to another with proper reactive power management [3] and to establish such condition, the injection and absorption of reactive power must be controlled efficiently. This can be realized by means of good power scheduling [4] and also a good reactive power support at load site via accurate shunt element installation (such as capacitor bank and shunt FACTS devices).

There are various methods available for selecting the most suitable generator bus to be performed power scheduling and the best location for shunt element placement at consumer site. The method can be sensitivity analysis [5], [6], stability index based analysis [7], [8], optimization technique [9], [10], 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 [11] and [12] 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. An algorithm for tracing the complex power among generators via bus impedance matrix (BIM) has been proposed by [13]. The complex power contributed by individual unit is performed by firstly tracing the contribution on voltage and current, with the product of the two will be the traced complex power. Unfortunately, the method still failed to provide free negative sharing among the participated generators. A simple formulation technique of power tracing via Genetic Algorithm (GA) has been proposed by [14], where it is considered as the first research that tries to adopt Artificial Intelligence (AI) optimization into power tracing field. Other research regarding on power tracing technique can be explored via [15] – [17]. 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

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of considering the application of the developed method into voltage stability field, for instance in power scheduling problem and shunt element placement (such as capacitor bank and shunt FACTS devices). Power scheduling consists of real power scheduling and reactive power control at generation site, where the purpose of doing such plan is to generate an economical amount of output powers to be injected with the enhancement of system stability concurrently. Article [18] applied Evolutionary Programming (EP) as a tool to perform optimal power scheduling involving both real and reactive power of generators. In the research, all generator's real and reactive powers have been sized via EP engine considering voltage stability and fuel cost to be spent. Optimal sizing of generator's real and reactive power via optimization method have also been proposed by [19] and [20], where both of the research have utilized Particle Swarm Optimization (PSO) algorithm for obtaining the finest amount of generators' power to be dispatched.

There are many ways for installing FACTS devices with optimal performance in terms of cost and system stability. Reference [21] 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 been conducted by [22], where STATCOM has been chosen as a tool for improving power system performance. A sensitivity analysis based FACTS device placement for improving static and transient stability has been explored by [23] 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 best generator bus to be performed power scheduling and the most suitable bus for shunt element placement considering 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 generator and load buses in the system that causes the highest level stress on a particular line. The stability index to be traced is called Fast Voltage Stability Index (*FVSI*) via Evolutionary Programming (EP).

2. MATHEMATICAL RELATIONSHIP FOR *FVSI*-TRACING (*FVSI*-T)

2.1 Fast Voltage Stability Index (*FVSI*)

Stability indices have been widely used in power system for the purpose of voltage stability assessment. They can be an indicator to indicate the condition of a power system whether healthy or stressed. I. Musirin [24] 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*) [25] and Line Stability Index (L_{mn}) [26], but the newness in *FVSI* is that it has been derived from quadratic equation and also easy to be utilized as the report in [24], [27] 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).

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

Where,

Z_l : line impedance
X_l : line reactance
Q_r : receiving end reactive power
V_s : sending end voltage

It is essential to note that the *FVSI* of a line should be less than unity in order that the voltage collapse can be prevented. For a clear illustration, Figure 1 depicts the fact.

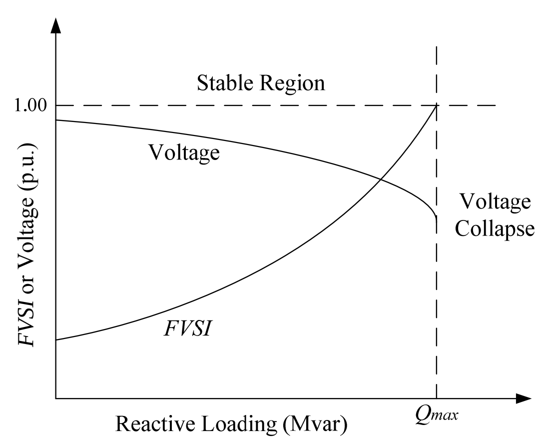

Figure 1. *FVSI* and voltage variation with respect to reactive loading

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As can be seen, for a stable power system before the occurrence of voltage collapse, the *FVSI* of all lines should be less than 1.00 or the reactive loading applied to a certain bus should be less than its maximum loadabilitiy, Q_{max}. This interpretation implies that a line with *FVSI* higher than unity has experienced a constraint violation because its capacity limit has been exceeded or to be more precise, the power system is now in stressed condition.

2.2 *FVSI*-Generation Tracing (*FVSI*-GT)

The purpose of tracing the stability index *FVSI* contributed by individual generator and 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 generator and load buses is the most suitable bus to be performed any corrective and preventive actions either under normal or contingencies condition. In other words, tracing the stability index can help the SO to select the generator and load buses according to their priority ranking based on the traced *FVSI*. This section will briefly described the technique for selecting the most suitable generator bus to be performed power scheduling by means of *FVSI*-GT, i.e. tracing the stability index *FVSI* on each line contributed by each generator in the system. The derivation of the modified *FVSI* equation of *l*-th line for the purpose of *FVSI*-GT is given below.

$$FVSI_l = FVSI_l^1 + FVSI_l^2 + \ldots + FVSI_l^{k,ngen} \tag{2}$$

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

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

$$\therefore FVSI_l = \frac{4Z_l^2}{V_s^2 X_l}\sum_{k=1}^{ngen} Q_r^k = \frac{4Z_l^2}{V_s^2 X_l}\sum_{k=1}^{ngen} x_r^k . Q_{gk} \tag{5}$$

Where,

- *ngen* : the number of reactive power sources in the system
- $Q_r^{\,k}$: receiving end reactive power contributed by *k*-th reactive source
- $x_r^{\,k}$: receiving end reactive power fraction contributed by *k*-th reactive source

Thus, the *FVSI* of a line contributed by an individual generator can be determined by simply tracing the receiving end reactive power of that line. Nevertheless, it is important to highlight that in the reactive power tracing point of view, the term reactive power sources (or reactive sources) is not only applied for generator, but also for other alternative sources such as capacitor bank, shunt capacitance of a line, and other shunt FACTS devices. From (5), it is revealed that the *FVSI* of *l*-th line contributed by *k*-th reactive source of power Q_{gk} can be mathematically represented as in (6).

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

By tracing the fraction x_r^k for all reactive sources, the priority ranking of generator bus for the purpose of economical power scheduling can be realized by means of calculating the traced $FVSI_l^{\,k}$ via (6).

2.3 *FVSI*-Load Tracing (*FVSI*-LT)

The procedures for tracing the *FVSI* contributed by system's loads are performed by the same token as in subsection 2.2, except now the term *ngen* and Q_{gk} in (2) to (6) are replaced by *nload* and Q_{Li} respectively. The significance of tracing the *FVSI* contributed by each load is to know which of the load buses in the system causes the highest congestion level to a particular transmission line. This also implies that if a certain load is identified as the major contributor of *FVSI* on a line (which has the highest traced *FVSI* value on that line), then the SO should take appropriate corrective actions such as capacitor bank or static Var compensator (SVC) installation as the load bus is insufficient reactive power support. The *FVSI* of *l*-th line contributed by *i*-th reactive power sink of power Q_{Li} is represented in (7), whereas equation (8) is for the total traced *FVSI* on *l*-th line.

$$FVSI_l^{Li} = \frac{4Z_l^2}{V_s^2 X_l}\left(x_r^i . Q_{Li}\right) \tag{7}$$

$$FVSI_l = \frac{4Z_l^2}{V_s^2 X_l}\sum_{i=1}^{nload} Q_r^i = \frac{4Z_l^2}{V_s^2 X_l}\sum_{i=1}^{nload} x_r^i . Q_{Li} \tag{8}$$

Where,

- *nload* : the number of reactive power sinks in the system
- $Q_r^{\,i}$: receiving end reactive power extracted by *i*-th reactive sink

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$x_r^{\ i}$: receiving end reactive power fraction extracted by *i*-th reactive sink

Again, it is essential to note that in the context of reactive power tracing, the term reactive power sinks (or reactive sinks) includes the system's loads, transmission lines that have reactive power flow coming from both ends, and generators that have negative reactive power generation.

2.4 Modification on shunt capacitance of transmission line

Actually, the receiving end power in (1) is not the power before entering the receiving end bus (Q'_r), instead, it is the receiving end power before passing the shunt capacitance node (Q_r), as illustrated below.

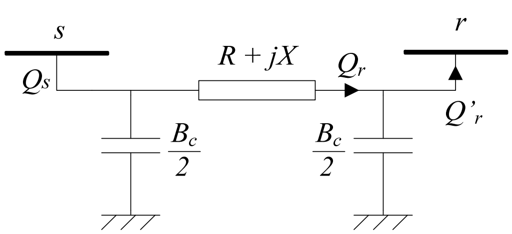
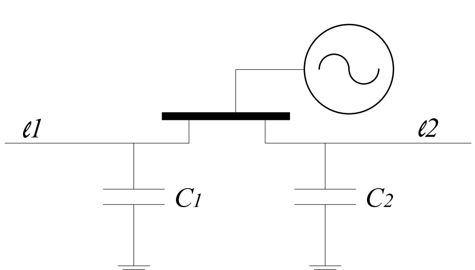


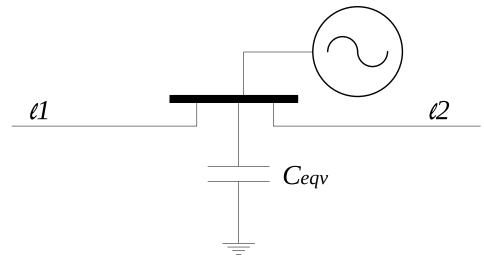
Figure 2. The receiving end power that will be used in *FVSI* is Q_r

It is rather difficult to formulate a power tracing algorithm that can trace the receiving end power before the shunt capacitance node. In virtue of that, alternative method for simplifying the shunt capacitances of all transmission lines connected at a particular bus is proposed in this research. The method is illustrated in Figure 3 (a) and (b), where the equivalent capacitance is equal to the summation of individual capacitances at that bus, i.e. $C_{eqv} = C_1 + C_2$.



(a)

Figure 3(a). Shunt capacitors before simplification



(b)

Figure 3(b). Equivalent shunt capacitors after simplification

3. EVOLUTIONARY PROGRAMMING (EP) BASED *FVSI*-TRACING (*FVSI*-T)

Pioneered by D. Fogel in 1962, the Evolutionary Programming (EP) was invented and upgraded for the purpose of optimization by Burgin. Due to unique solution after convergence and simple formulation steps offered by EP, this research decided to choose the algorithm for performing the optimization on *FVSI*-T.

3.1 Formulation Technique

Prior to performing the developed *FVSI*-T 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. After conducting a lot of studies regarding on optimization method, the best way to formulate the EP into *FVSI*-T problem is presented below.

i) Control Variables: The control variables in the context of *FVSI*-T is represented by the receiving end fraction $x_r^{\ k}$ (or $x_r^{\ i}$) and reactive sink fraction $x_{Li}^{\ k}$ (or reactive source fraction $x_{gk}^{\ i}$) contributed by generators (or loads) in the system. For simplicity, all of the fractions are placed in a matrix $\boldsymbol{X}$, which also represents an EP's *b*-th individual. This implies that if the developed EP engine requires population size of fifty, then the optimization engine consists of fifty matrices $\boldsymbol{X}$. It should be noted that the size of the matrix $\boldsymbol{X}$ depends on the type of *FVSI*-T, either *FVSI*-GT or *FVSI*-LT. The sizes of matrix $\boldsymbol{X}$ are (*nbr* + *nload*) x *ngen* and (*nbr* + *ngen*) x *nload* for both *FVSI*-GT and *FVSI*-LT respectively. The term *nbr* stands for the number of transmission lines in the system. A *b*-th matrix $\boldsymbol{X}$ for the purpose of *FVSI*-GT is given in (9).

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$$\boldsymbol{X}=\begin{bmatrix} x_{r1}^{1} & \cdots & x_{r1}^{k} & \cdots & x_{r1}^{ngen} \\ x_{r2}^{1} & & x_{r2}^{k} & & x_{r2}^{ngen} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{rl}^{1} & & x_{rl}^{k} & & x_{rl}^{ngen} \\ \vdots & & \vdots & & \vdots \\ x_{r,nbr}^{1} & \cdots & x_{r,nbr}^{k} & \cdots & x_{r,nbr}^{ngen} \\ x_{L1}^{1} & & x_{L1}^{k} & & x_{L1}^{ngen} \\ x_{L2}^{1} & & x_{L2}^{k} & & x_{L2}^{ngen} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{Li}^{1} & & x_{Li}^{k} & & x_{Li}^{ngen} \\ \vdots & & \vdots & & \vdots \\ x_{L,nload}^{1} & \cdots & x_{L,nload}^{k} & \cdots & x_{L,nload}^{ngen} \end{bmatrix} \tag{9}$$

ii) Constraints: The well known equality and non-equality constraints according to [16] that should be specified in the developed EP engine are as follows. Equation (10) – (12) is for *FVSI*-GT, whereas equation (13) – (15) is for *FVSI*-LT.

$$Q_r=\sum_{k=1}^{ngen} x_r^k . Q_{gk} \tag{10}$$

$$Q_{Li}=\sum_{k=1}^{ngen} x_{Li}^k . Q_{gk} \tag{11}$$

$$0 \le x_r^k, x_{Li}^k, x_{loss}^k \le 1 \tag{12}$$

$$Q_r=\sum_{i=1}^{nload} x_r^i . Q_{Li} \tag{13}$$

$$Q_{gk}=\sum_{i=1}^{nload} x_{gk}^i . Q_{Li} \tag{14}$$

$$x_r^i, x_{gk}^i, x_{loss}^i \ge 0 \tag{15}$$

The variable x_{loss} in (12) and (15) represents the fraction of losses on a particular line contributed by generators and loads respectively.

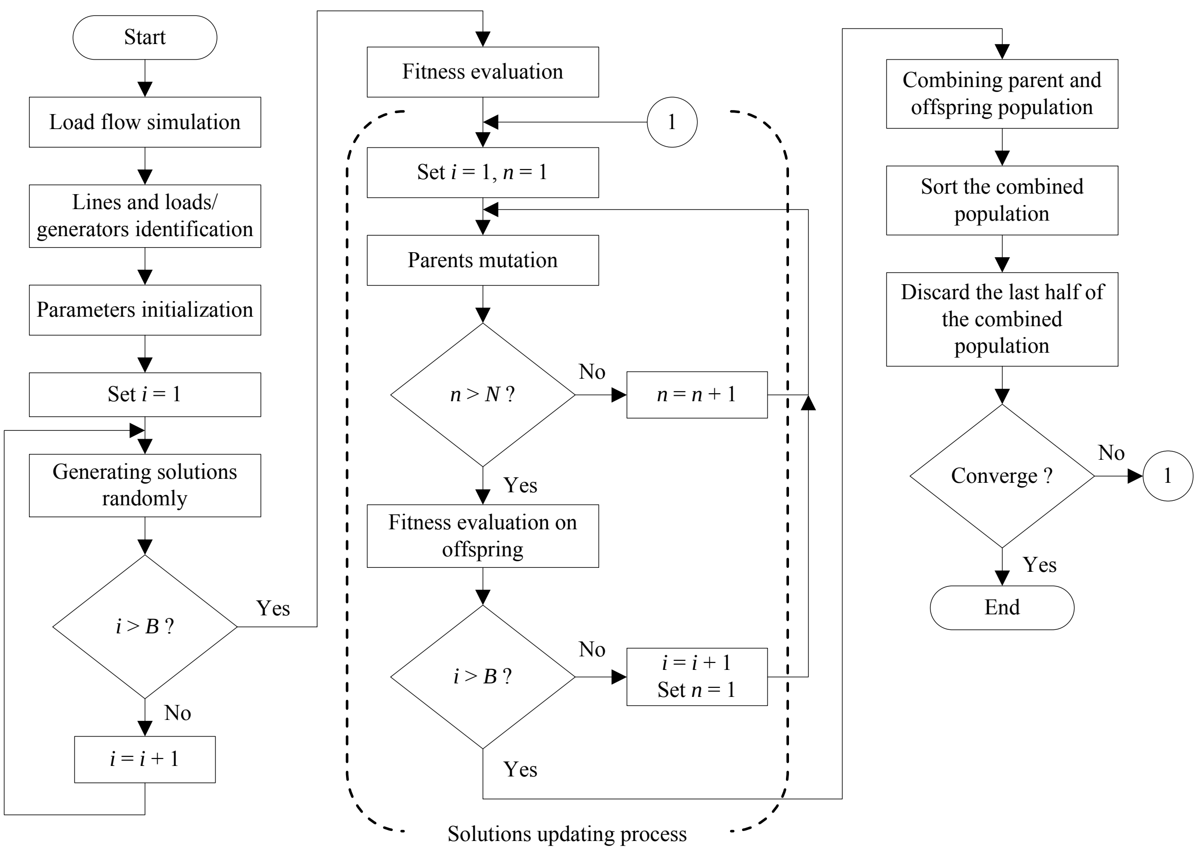

Figure 4. Complete algorithm for EP based *FVSI*-T

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iii) Objective Function: A hypothetical equation has been derived to be utilized as the fitness for guiding the EP algorithm. The objective functions for both *FVSI*-GT and *FVSI*-LT have been derived from the individual power balance equation of generator and load, as in (16) and (17) respectively. After several derivation and simplification as in [28], the objective functions to be utilized in EP engine for both *FVSI*-GT and *FVSI*-LT are represented by (18) and (19) respectively.

$$Q_{gk} = \sum_{i=1}^{nload} Q_{Li}^{k} + \sum_{l=1}^{nbr} Q_{loss,l}^{k} \qquad (16)$$

$$Q_{Li} = \sum_{k=1}^{ngen} Q_{gk}^{i} - \sum_{l=1}^{nbr} Q_{loss,l}^{i} \qquad (17)$$

$$E_{gk}(x) = 1 - \sum_{i=1}^{nload} x_{Li}^{k} - \sum_{l=1}^{nbr} x_{loss,l}^{k} \qquad (18)$$

$$E_{Li}(x) = \sum_{k=1}^{ngen} x_{gk}^{i} - \sum_{l=1}^{nbr} x_{loss,l}^{i} - 1 \qquad (19)$$

In the above equations, both $E_{gk}(x)$ and $E_{Li}(x)$ will be minimized as low as possible by EP search engine until their value approach zero. After determining the best way to formulate the EP parameters and components into *FVSI*-T problem, the complete algorithm has been developed before implementing into source code, as illustrated in Figure 4. The equation for mutation of EP can be explored in [18] and [24].

4. RESULTS AND DISCUSSION

The developed EP 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 Generation and Load Distribution Factor (TGLDF) which is proposed by [11], [12] and other non-*FVSI*-T method which is Loss Sensitivity (LS) technique.

4.1 Comparison for *FVSI*-Generation Tracing (*FVSI*-GT)

Table 1 and 2 tabulate the traced *FVSI* contributed by the individual reactive sources in 14-bus system, i.e. four generators (G2, G3, G4, and G5) and two capacitor banks (C6 and C8).

As can be seen, both methods are able to trace the *FVSI* contributed by individual reactive source from all transmission lines. However, by looking at the total value of *FVSI* for each line, it is seen that there is much difference between the two methods. For instance, the total *FVSI* for line number 1, ℓ1 are 0.110 and 0.204 for EP and TGDF based *FVSI*-GT respectively. This is because the EP based method performs an actual value based *FVSI*-GT, which means that the method used all of the original power flow results (actual power flow values) to trace the contributed *FVSI*. On the contrary, the TGDF method performs gross value based *FVSI*-GT, which implies that when performing the tracing task, the traced *FVSI* is

Table 1. *FVSI*-GT Results for 14-Bus System via EP

Line	G2	G3	G4	G5	C6	C8	Total
ℓ1	0.085	0.006	0.007	0.006	0.004	0.002	0.110
ℓ2	0.000	0.008	0.002	0.012	0.003	0.002	0.027
ℓ3	0.000	0.059	0.000	0.000	0.000	0.000	0.059
ℓ4	0.000	0.013	0.025	0.011	0.005	0.000	0.054
ℓ5	0.000	0.002	0.008	0.007	0.009	0.008	0.033
ℓ6	0.000	0.037	0.000	0.000	0.000	0.000	0.037
ℓ7	0.000	0.006	0.009	0.007	0.003	0.000	0.024
ℓ8	0.000	0.000	0.000	0.109	0.000	0.000	0.109
ℓ9	0.000	0.000	0.015	0.003	0.000	0.000	0.018
ℓ10	0.000	0.000	0.147	0.000	0.000	0.000	0.147
ℓ11	0.000	0.000	0.075	0.000	0.000	0.000	0.075
ℓ12	0.000	0.000	0.028	0.000	0.000	0.000	0.028
ℓ13	0.000	0.000	0.055	0.000	0.000	0.000	0.055
ℓ14	0.000	0.000	0.000	0.219	0.000	0.000	0.219
ℓ15	0.000	0.000	0.000	0.082	0.000	0.000	0.082
ℓ16	0.000	0.000	0.001	0.000	0.000	0.000	0.001
ℓ17	0.000	0.000	0.001	0.004	0.000	0.000	0.004
ℓ18	0.000	0.000	0.056	0.000	0.000	0.000	0.056
ℓ19	0.000	0.000	0.031	0.000	0.000	0.000	0.031
ℓ20	0.000	0.000	0.080	0.000	0.000	0.000	0.080

Note: 'G' and 'C' means generator and capacitor bank respectively.

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Table 2. *FVSI*-GT results for 14-Bus System via TGDF

Line	G2	G3	G4	G5	C6	C8	Total
ℓ1	0.114	0.034	0.014	0.027	0.011	0.003	0.204
ℓ2	0.000	0.015	0.131	0.059	0.024	0.029	0.258
ℓ3	0.000	0.106	0.000	0.000	0.000	0.000	0.106
ℓ4	0.000	0.020	0.000	0.080	0.033	0.000	0.133
ℓ5	0.000	0.006	0.051	0.023	0.010	0.011	0.100
ℓ6	0.000	0.038	0.000	0.000	0.000	0.000	0.038
ℓ7	0.000	0.004	0.000	0.018	0.007	0.000	0.030
ℓ8	0.000	0.000	0.000	0.135	0.000	0.000	0.135
ℓ9	0.000	0.000	0.001	0.058	0.000	0.000	0.059
ℓ10	0.000	0.000	0.198	0.000	0.000	0.000	0.198
ℓ11	0.000	0.000	0.077	0.000	0.000	0.000	0.077
ℓ12	0.000	0.000	0.030	0.000	0.000	0.000	0.030
ℓ13	0.000	0.000	0.058	0.000	0.000	0.000	0.058
ℓ14	0.000	0.000	0.000	0.233	0.000	0.000	0.233
ℓ15	0.000	0.000	0.000	0.093	0.000	0.000	0.093
ℓ16	0.000	0.000	0.002	0.000	0.000	0.000	0.002
ℓ17	0.000	0.000	0.000	0.009	0.000	0.000	0.009
ℓ18	0.000	0.000	0.058	0.000	0.000	0.000	0.058
ℓ19	0.000	0.000	0.033	0.000	0.000	0.000	0.033
ℓ20	0.000	0.000	0.087	0.000	0.000	0.000	0.087

Note: 'G' and 'C' means generator and capacitor bank respectively.

determined from the gross value of the receiving end power flow (not the actual power from power flow results). The priority ranking based on the traced *FVSI* for both methods is tabulated in Table 3.

For the case involving 14-bus system, both EP and TGDF method provide identical ranking results for generator bus. The interpretation that can be deduced from Table 3 is that for the purpose of selecting the generator bus to be performed economic dispatch or power scheduling, an SO should firstly choose the generator at bus 5 as it becomes the major contributor of *FVSI* on line ℓ14 (with contributed *FVSI* of 0.219) . This is followed by generator at bus 4, 2, and finally 3. Although the priority ranking can also be performed without *FVSI*-GT (which means that by calculating only the *FVSI* of each line via (1) without tracing method), the method is only applicable for 14-bus system. For 57-bus system as in Table 4, calculation of *FVSI* via (1) without *FVSI*-GT cannot provide reliable signal for SO. For example, the line ℓ64 for TGDF method has the highest *FVSI* value, but it does not come from the buses connecting this line (bus 13 and 49), instead, the *FVSI* comes majorly from bus 12. This is similar to ℓ52, ℓ34, ℓ65 and ℓ68 for both methods. Meanwhile, contrary to EP and TGDF method, the LS method (non-*FVSI*-GT) results to totally different priority ranking for generator bus in both systems. The LS method provides unreliable signal for SO about the major contributor of *FVSI* on a particular transmission line, for example, the major contributors of *FVSI* or the most suitable generators for power scheduling according to this method are generator at bus 2 and 3 for 14 and 57-bus respectively.

Table 3. Generator Bus Priority Ranking for 14-Bus System

EP					TGDF					LS
Gen. Bus	Line	From	To	*FVSI*-T	Gen. Bus	Line	From	To	*FVSI*-T	Gen. Bus
5	ℓ14	5	7	0.2190	5	ℓ14	5	7	0.2325	2
4	ℓ10	4	8	0.1469	4	ℓ10	4	8	0.1978	4
2	ℓ1	2	1	0.0849	2	ℓ1	2	1	0.1144	3
3	ℓ3	3	2	0.0593	3	ℓ3	3	2	0.1063	5

Table 4. Generator Bus Priority Ranking for 57-Bus System

EP					TGDF					LS
Gen. Bus	Line	From	To	*FVSI*-T	Gen. Bus	Line	From	To	*FVSI*-T	Gen. Bus
12	ℓ11	12	9	0.1068	12	ℓ64	13	49	0.1210	3
9	ℓ52	11	41	0.0370	3	ℓ2	3	2	0.0669	12
3	ℓ2	3	2	0.0213	8	ℓ34	24	25	0.0529	9
8	ℓ34	24	25	0.0196	9	ℓ68	55	54	0.0491	6
6	ℓ65	29	52	0.0117	6	ℓ34	24	25	0.0233	8

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4.2 Comparison for *FVSI*-Load Tracing (*FVSI*-LT)

Meanwhile, the traced *FVSI* contributed by reactive sinks for 14-bus system are tabulated in Table 5 and 6 for EP and TLDF method respectively.

Again, 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 similar reason as in subsection 4.1 is applicable for this case where the EP 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 reactive source'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 EP. The load buses priority ranking for 14-bus system is tabulated in Table 7. 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 EP and ℓ1 for TLDF). To be more precise, load at bus 1 being the major contributor for the high

Table 5. *FVSI*-LT Results for 14-Bus System via EP

Line Number	Load Buses 1	2	8	9	10	11	12	13	14	Total
ℓ1	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.110
ℓ2	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027
ℓ3	0.056	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.059
ℓ4	0.040	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
ℓ5	0.027	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033
ℓ6	0.033	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.037
ℓ7	0.007	0.010	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.024
ℓ8	0.107	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.109
ℓ9	0.016	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.018
ℓ10	0.060	0.064	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.147
ℓ11	0.055	0.003	0.004	0.007	0.002	0.001	0.000	0.000	0.002	0.075
ℓ12	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.025	0.002	0.028
ℓ13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.036	0.055
ℓ14	0.125	0.083	0.003	0.007	0.000	0.000	0.000	0.000	0.001	0.219
ℓ15	0.069	0.005	0.000	0.003	0.000	0.000	0.000	0.000	0.004	0.082
ℓ16	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
ℓ17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004
ℓ18	0.005	0.002	0.002	0.006	0.010	0.000	0.000	0.000	0.030	0.056
ℓ19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.005	0.031
ℓ20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080

Table 6. *FVSI*-LT Results for 14-Bus System via TLDF

Line Number	Load Buses 1	2	8	9	10	11	12	13	14	Total
ℓ1	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.110
ℓ2	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027
ℓ3	0.035	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.046
ℓ4	0.032	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042
ℓ5	0.020	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
ℓ6	0.008	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.011
ℓ7	0.004	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.006
ℓ8	0.024	0.006	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.033
ℓ9	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005
ℓ10	0.024	0.003	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.034
ℓ11	0.000	0.000	0.000	0.003	0.053	0.017	0.000	0.000	0.000	0.073
ℓ12	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.009	0.028
ℓ13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.024	0.054
ℓ14	0.019	0.005	0.002	0.098	0.000	0.000	0.000	0.000	0.002	0.126
ℓ15	0.001	0.000	0.000	0.069	0.000	0.000	0.000	0.000	0.001	0.072
ℓ16	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
ℓ17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004
ℓ18	0.000	0.000	0.000	0.003	0.052	0.000	0.000	0.000	0.000	0.055
ℓ19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.013	0.030
ℓ20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080

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Table 7. Load Buses Priority Ranking for 14-Bus System

EP					TLDF					LS
Load bus	Line number	From	To	*FVSI*-T	Load bus	Line number	From	To	*FVSI*-T	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

Table 8. Load Buses Priority Ranking for 57-Bus System

EP					TLDF					LS
Load Bus	Line number	From	To	*FVSI*-T	Load Bus	Line number	From	To	*FVSI*-T	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

congestion level of the system. The best location after bus 1 for shunt element installation should be bus 2 and bus 9 for EP 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), but the results might be inaccurate. For instance, in the last column of Table 5 and 6, 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 preventive actions. However, the results provided by tracing method show that among the top priority ranking in Table 7, 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 8, which tabulates the load buses priority ranking results for 57-bus system, is also applicable.

Again, the non-*FVSI*-LT method, i.e. LS still results to different priority ranking for load buses in both systems as compared to EP and TLDF method. This implies that the LS method is unable to be a sophisticated indicator for an SO when confronting with the problems related to voltage stability assessment and improvement.

For further justification regarding on the reliability and effectiveness of the proposed *FVSI-T*, article [29] is recommended.

5. CONCLUSION

This paper has presented a new technique for identifying the most suitable generator and load buses for the purpose of preventive and corrective actions by means of *FVSI*-T. The method has promoted a reliable technique for ranking the priority of generator bus to be performed power scheduling and load buses for shunt element installation accurately. This can be valuable knowledge for a system operator (SO) when confronting with a problem related to voltage stability assessment and improvement. The SO can decide intelligently for any actions based on the information provided by the *FVSI*-T results, which means that operator's intuitive decision is no longer needed. Moreover, the Artificial Intelligence (AI) based *FVSI*-T via Evolutionary Programming (EP) has also been promoted in this paper and the results using the developed EP algorithm is comparable to the alternative technique such as Topological Generator and Load Distribution Factor (TGLDF) method.

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