Improving the AC Transmission Expansion Planning by Using Initial Solutions Algorithms

Nelson E. Matute [1], Santiago P. Torres[2], Edgar G. Morquecho[3], Fabian Astudillo-Salinas[4], Julio C. Lopez[5], Wilfredo C. Flores[6]

[1-5]Department of Electrical, Electronics and Telecommunications Engineering, *University of Cuenca, Cuenca, Ecuador*
[6]Facultad de Ingeniería, *Universidad Tecnológica Centroamericana (UNITEC), Tegucigalpa, Honduras,11101*
[1]nelson.matute@ucuenca.edu.ec, [2]santiago.torres@ucuenca.edu.ec, [3]edgarmorquecho@hotmail.com

***Abstract*—Initial Solutions (IS) are decisive in meta-heuristics based optimization problems since they impact the performance of the optimization process. This research work proposes and compares some random and deterministic algorithms to create initial solutions based on existing expansion planning criteria to solve the AC Transmission Expansion Planning (TEP) problem. The TEP is formulated as a full non-convex optimization problem using the AC network representation. A local version of the Particle Swarm Optimization (LPSO) technique is employed to solve the TEP problem. The Garver 6-bus and IEEE 24-bus test systems are used to evaluate the IS algorithms performance. It is shown that these algorithms have great potential to improve the robustness and computational effort of meta-heuristics.**

***Index Terms*—AC model, electric power systems, transmission expansion planning, initial solutions, least-effort criterion.**

I. Introduction

The Transmission Expansion Planning (TEP) is very important for the proper development of sustainable Electric Power Systems (EPS). The increase in the TEP complexity leads to find new ways to solve the problem straightforward and more efficiently. When the TEP is solved using meta-heuristics algorithms, they start from initial candidate solutions. Then, the meta-heuristic technique seeks the best possible solution in terms of its objective function. The performance of the optimization techniques depends on the used method and the Initial Solutions (IS) quality. Therefore, to enhance the optimization process performance, both IS quality and meta-heuristics methods (optimization techniques) should be improved. Currently, most of literature focuses on refining the optimization techniques, only using random methods as Initial Solutions Algorithm (ISA) [1], [2]. In [3], IS are created by adding to the base topology the branch that carries the highest power flow until finding a feasible topology. In [4], a sensitivity index corresponding to the circuit that transports the highest power flow is proposed to find the most attractive network topology. In [5], the proposed IS algorithm uses expansion parameters based on the weighting of various sensitivity indexes. There are no performance comparisons among algorithms in the mentioned works. This research work improves, compares, and adapts some ISAs to the AC formulation. The goal is to solve the TEP problem more efficiently. This article is organized as follows: The mathematical formulation is presented in Section II. Section III presents the ISAs. Section IV shows the results of Garver 6-bus and IEEE 24-bus. Finally, conclusions and future research work are presented in Section V.

II. Mathematical Formulation

The mathematical AC model formulation of TEP is separated into two sub-problems: i) the economical TEP approach and ii) the operational EPS sub-problem.

The economical TEP problem considers the costs of adding transmission circuits and the cost of load shedding. It is formulated as follows:

$$\min w = \sum_{(k,l)\in\boldsymbol{\Omega}} (c_{kl} n_{kl}) + c_{ls} \tag{1}$$

subject to

$$0 \leq \boldsymbol{n} \leq \overline{\boldsymbol{n}} \tag{2}$$
$$n_{kl} \in \mathbb{Z}$$

where w is the total investment cost of new transmission circuits plus the load shedding cost; c_{kl} and n_{kl} are the costs of adding and the integer number of new circuits between the buses k-l, respectively; c_{ls} represents the total cost of load shedding (in case that load shedding is allowed in the final plan). $\boldsymbol{\Omega}$ represents the set of all rights-of-ways (candidates transmission paths); $\boldsymbol{n}$ represents a vector of the number of existing and new circuits in the current topology; $\overline{\boldsymbol{n}}$ is a vector of the maximum number of circuits allowed for all n_{kl} in $\boldsymbol{\Omega}$.

The operational sub-problem is formulated as follows:

$$\min c_{ls} = \sum_{k\in\Gamma} (\alpha_1 r_{P_k} + \alpha_2 r_{Q_k}) \tag{3}$$

subject to

$$\boldsymbol{P}(\boldsymbol{V},\boldsymbol{\Theta}) - \boldsymbol{P}_G - \boldsymbol{r}_P + \boldsymbol{P}_D = 0 \tag{4}$$
$$\boldsymbol{Q}(\boldsymbol{V},\boldsymbol{\Theta}) - \boldsymbol{Q}_G - \boldsymbol{r}_Q + \boldsymbol{Q}_D = 0 \tag{5}$$
$$\underline{\boldsymbol{P}}_G \leq \boldsymbol{P}_G \leq \overline{\boldsymbol{P}}_G \tag{6}$$
$$\underline{\boldsymbol{Q}}_G \leq \boldsymbol{Q}_G \leq \overline{\boldsymbol{Q}}_G \tag{7}$$
$$\underline{\boldsymbol{r}}_P \leq \boldsymbol{r}_P \leq \overline{\boldsymbol{r}}_P \tag{8}$$
$$\underline{\boldsymbol{r}}_Q \leq \boldsymbol{r}_Q \leq \overline{\boldsymbol{r}}_Q \tag{9}$$
$$\underline{\boldsymbol{V}} \leq \boldsymbol{V} \leq \overline{\boldsymbol{V}} \tag{10}$$
$$\boldsymbol{S}^{from} \leq \overline{\boldsymbol{S}} \tag{11}$$
$$\boldsymbol{S}^{to} \leq \overline{\boldsymbol{S}} \tag{12}$$

$$(\boldsymbol{\Theta}_k, \boldsymbol{\Theta}_l) \in \mathbb{R}$$

The operational optimization sub-problem minimizes the total cost of load shedding c_{ls}. The load shedding is modeled by adding Fictitious Generators (FG) of active and reactive power to the load buses; their operation cost is calculated by using (3). The terms $\boldsymbol{r}_P$ and $\boldsymbol{r}_Q$ model the load shedding; these are vectors of active and reactive power of FG, respectively; α_1 and α_2 are penalty coefficients due to the contribution of FG of active and reactive power, respectively; $\boldsymbol{\Gamma}$ is the set of all buses where there is electrical demand (either active or reactive). $\boldsymbol{P}(\boldsymbol{V}, \boldsymbol{\Theta})$ and $\boldsymbol{Q}(\boldsymbol{V}, \boldsymbol{\Theta})$ are active and reactive power flow vectors; $\boldsymbol{\Theta}$ and $\boldsymbol{V}$ are the phase angle and voltage magnitude vectors; $\boldsymbol{P}_G$ and $\boldsymbol{Q}_G$ are the existing generation of active and reactive power vectors, respectively; $\boldsymbol{P}_D$ and $\boldsymbol{Q}_D$ are the active and reactive power demand vectors. $\underline{\boldsymbol{P}}_G$, $\underline{\boldsymbol{Q}}_G$, $\underline{\boldsymbol{r}}_P$, $\underline{\boldsymbol{r}}_Q$, and $\underline{\boldsymbol{V}}$ are the vectors of minimum limits of existing active and reactive power generation, active and reactive load shedding, and voltage magnitudes, respectively. $\overline{\boldsymbol{P}}_G$, $\overline{\boldsymbol{Q}}_G$, $\overline{\boldsymbol{r}}_P$, $\overline{\boldsymbol{r}}_Q$, and $\overline{\boldsymbol{V}}$ are the vectors of maximum limits of existing active and reactive power generation, active and reactive load shedding, and voltage magnitudes, respectively. $\boldsymbol{S}^{from}$ and $\boldsymbol{S}^{to}$, are the vectors of apparent power flows [MVA] through the branches in both directions, k-l and l-k, respectively; $\overline{\boldsymbol{S}}$ is the vector of maximum limits of apparent power [MVA] through branches. The equations of $\boldsymbol{P}(\boldsymbol{V}, \boldsymbol{\Theta})$, $\boldsymbol{Q}(\boldsymbol{V}, \boldsymbol{\Theta})$, $\boldsymbol{S}^{from}$, and $\boldsymbol{S}^{to}$ can be found in [2].

In this work, active load shedding is not allowed in the final plan ($r_P = 0$), and all scenarios consider unlimited reactive power sources without shunt compensation cost ($\alpha_2 = 0$). The operational feasibility of any candidate solution, referred as Function Evaluation (FE), is calculated by an AC-OPF using (3)-(12), for each transmission topology in the current population. A more detailed explanation about active and reactive load shedding in this TEP formulation can be found in [2].

III. Initial solution algorithms

The algorithms of the traditional and percentage methods are based on random parameters; therefore, they are called Random Algorithms (RA). On the other hand, backward, forward, least-effort, and overload methods are Deterministic Algorithms (DA). DA provides a population of only one individual and stops the process if at least a cost solution is reached; if not, the percentage algorithm is used to create the other individuals. The last procedure provides a diverse initial population so that the incoming optimization algorithm (meta-heuristic) does not stagnate in a local optimum due to diversity loss.

A. Traditional Algorithm

The traditional algorithm is a random method uniformly distributed. It creates, inside the search space, some circuits for each right-of-way, i.e., between the existing lines of the base topology and the maximum number of branches allowed $\overline{\boldsymbol{n}}$ for each right-of-way in $\boldsymbol{\Omega}$. This method is standard for most optimization problems [6].

B. Percentage Algorithm

The percentage algorithm is an improved version of the traditional method. It limits the total number of right-of-ways to be modified by circuit additions. It was proposed in [2].

C. Least-Effort Criterion Variant

The least-effort criterion [7] is a transmission planning aid. It takes into account the flow distribution pattern in the network. The least-effort path is the one that best distributes the system power flows. It is selected using the greatest sensitivity index of all right-of-ways. Thus, at each iteration, a new circuit is added to the least-effort path. It repeats until to find a feasible topology. The least-effort index is calculated by using (13). Where $\boldsymbol{\sigma_i}^{le}$ is the set of the least-effort values for each $i \in \boldsymbol{\Omega}$, γ_i is the series susceptance of the branch i in $\boldsymbol{\Omega}$, and θ_i is the angle across the branch i before the circuit addition (previous topology) for each $i \in \boldsymbol{\Omega}$. In this work, the series susceptance γ_{kl}, between the buses k-l, is calculated by (14), where X_{kl} and R_{kl} are the series reactance and resistance of the branch, respectively. A further explanation of the original method can be found in [7].

$$\boldsymbol{\sigma_i}^{le} = -\frac{1}{2}\gamma_i \theta_i^2 \tag{13}$$

$$\gamma_{kl} = -\frac{X_{kl}}{R_{kl}^2 + X_{kl}^2} \tag{14}$$

The complete procedure of the least-effort criterion variant used in this work is described by Algorithm 1. This variant is adapted and improved to be used with the AC power flow model and FG.

Algorithm 1 Least-Effort Criterion Variant

Set the number of circuits limits x_i^{min} and x_i^{max} $\forall i \in \boldsymbol{\Omega}$.
Set current topology as initial topology $x_i = x_i^{min}$.
Solve the AC optimal power flow and evaluate x_i.
while $c_{ls} \neq 0$ **do**
  Calculate the least-effort indexes $\boldsymbol{\sigma}_i^{le}$ by using (13). Then, calculate the benefit/cost ratios $\boldsymbol{\beta}_i^{le} = |\boldsymbol{\sigma_i}^{le}/c_{kl}|$ $\forall i \in \boldsymbol{\Omega}$.
  Determine the possible circuits additions and add to the least-effort path the branch that corresponds to the highest absolute value of $\boldsymbol{\beta}^{le}$.
  Solve the AC optimal power flow and evaluate x_i with the new addition.
end while
Sort the new circuit additions by descending $\boldsymbol{\beta}^{le}$ ratio (corresponding to the last topology) and eliminate unnecessary circuits whose removal does not produce load shedding.

D. Backward and Forward Methods [8]

The backward method is a regressive heuristic method, which starts with the maximum number of allowed candidates circuits within the search space (feasible region). Then, the circuits are removed one-by-one from the network, resulting in $\|\boldsymbol{\Omega}\|$ topologies and FE. At the current iteration, the most feasible topology is adopted based on the lowest TEP cost w; it is produced by FE without load shedding. The most feasible topology becomes the initial topology for the next iteration. This procedure is repeated until finding unfeasible topologies. As a result, the least-cost feasible topology has found.

The forward method is a progressive heuristic method. It starts with the base case transmission topology, without circuit additions. As expected, the base case topology is outside the feasible region; therefore, circuits are added one-by-one, resulting in $\|\mathbf{\Omega}\|$ topologies and FE. The topology that produces the lower TEP cost w becomes the next starting topology. This procedure ends up with the least-cost feasible topology (no-load shedding). A full explanation of the backward and forward methods can be found in [8].

The least-effort, backward, forward, and overload methods use the AC optimal power flow; it is solved by using a prime-dual interior-point method using MATPOWER [9]. As a result, these algorithms determine whether a topology is feasible, taking into account the load shedding only, which represents any constraint violation (4)-(12). Additionally, the following method does not take into account the overload in branches.

E. Overload Criterion

The overload criterion is a well-known aid in the transmission expansion planning practice. In this work, this criterion is used to create initial solutions and adapted to work with the AC formulation, including fictitious generators. This method works with two simultaneous topologies: a fictitious and a current topology. The fictitious topology x_i^* results from the addition of branches to each right-of-way that does not have any transmission circuit. Whereas the current topology x_i is the base case topology. Then, at each iteration, a circuit is added to each overloaded right-of-way in the current topology x_i, based on the power flow values. Indeed, more than a circuit can adds in each iteration if there is more than an overloaded path. In each iteration, x_i^* is updated taking into account the new circuit (x_i). If the new circuits corresponds to a x_i^* branch, added as a fictitious branch, it becomes a real branch (no circuit addition needed); otherwise, the topology x_i^* is updated adding a real branch to the respective overload path.

The overloads in branches are calculated using the AC optimal power flow tool from MATPOWER, considering branches capacity unlimited. The overloads are penalized in the same way as FG operation. The search process ends up with the most feasible topology, whose FE produces a penalization flag Ψ equal to zero. Then, the resulting topology starts an elimination process, ranking the new circuit additions by benefit/cost ratio and removing all the unnecessary circuits whose elimination does not produce penalization. Algorithm 2 shows the complete steps of this method.

Algorithm 2 Overload Criterion

Set the number of circuits limits x_i^{min} and x_i^{max} $\forall i \in \mathbf{\Omega}$
Set current topology as initial topology $x_i = {x_i}^{min}$
Set fictitious topology as initial topology $x_i^* = {x_i}^{min}$
If initial topology has candidate paths without circuits; then, a single circuit is added to each path of the fictitious topology x_i^* with no circuits.
Turn off all active power fictitious generators.
Solve the AC power flow without considering the branch flow limits [(11) and (12)]. Then, evaluate both x_i and x_i^*.
For x_i topology, either: i) if the AC power flow does not converge, or ii) if the branches power flow restrictions are not satisfied [(11) and (12)], set a penalization flag $\Psi \neq 0$.
while $\Psi \neq 0$ **do**
    If the total flows through fictitious circuits $S^* = \max(\mid S^{from*} \mid, \mid S^{to*} \mid)$ are higher than the MVA limits per circuit, for each right of way $S^* > \overline{S}$; then, a circuit is added to all overloaded paths for x_i. Also, a circuit is added in all overloaded paths where x_i^* has the same number of circuits than x_i.
    Solve the AC power flow without considering (11) and (12). Evaluate the topologies x_i and x_i^*. If Ψ, corresponding to x_i, is equal to zero; then, stop the process.
    Set power flows of fictitious topology equal to current flows on paths where current flow is not zero: $S_i^* = S_i$, $\forall i$ where $S_i \neq 0$.
end while
Calculate the (unit flow)/cost ratios: $\boldsymbol{\beta}_i^{ol} = S_i/c_i$ for the new circuit additions corresponding to x_i resulting topology.
Sort the new circuit additions by descending $\boldsymbol{\beta}^{ol}$ ratio and eliminate unnecessary circuits whose removal does not produce penalization.

IV. Test Results

The Garver 6-bus and IEEE 24-bus test systems have been analyzed. These systems are commonly used in the TEP problem as benchmark networks. The complete data can be found in [4] or can be provided upon request. In this research work, four scenarios have been analyzed: 1) Garver 6-bus dispatchable generation *A_1*; 2) Garver 6-bus non-dispatchable generation *A_2*; 3) IEEE 24-bus dispatchable generation *B_1*; and 4) IEEE 24-bus non-dispatchable generation *B_2*.

The non-dispatchable scenarios modify the flexibility of existing generators, forcing them to work with predefined fixed generation. On the other hand, the following considerations were assumed for all scenarios: i) active load shedding is not allowed ($r_p = 0$); ii) unlimited reactive power sources are considered in load buses without reactive cost ($\alpha_2 = 0$); iii) the minimum and maximum voltage magnitude limits are set to 95% and 105% of the nominal value; (iv) a maximum of five circuits per right-of-way was established; and (v) the percentage algorithm parameter is set to 10% for all scenarios except for scenario *A_2*, where it is 20%.

The algorithms were implemented in MATLAB 8.3 and computed on a hardware platform with the following specifications: Intel 7 Core i7, 2.8 GHz, 12 GB RAM. The power flow tools from MATPOWER 6.0 were also used.

A. Garver 6-bus system

Garver 6-bus system consists of 15 right-of-ways, an isolated node, a total load of 760 MW and 152 MVAr, and a total active power generation of 1140 MW. For scenarios *A_1* and *A_2*, a population N of 60 individuals with a maximum of 100 iterations was considered. Also, the number of trials was 10.

1) Dispatchable generation: For the Scenario *A_1*, Table I shows four different feasible topologies that have the same expansion cost. Solution *S1* agrees with the solution found in [4]. Solution *S3* is the most found in the literature and agrees with the resulting topology found in [2] using the AC model, [3] using the DC model, and some others. Solution *S4* agrees with the topology found in [1]. Nevertheless, solution *S2* is a new feasible topology found in this work for Garver 6-bus system considering re-dispatch. Each solution was attained by the following ISAs: *S1*: III-A, III-B, and III-C; *S2*: III-A and III-B; *S3*: III-A, III-B, and III-D; *S4*: III-A, III-B, and III-E. The best found solution for this scenario corresponds to an investment cost equal to $w =$ US$ 110, and the transmission circuits added to the base topology for each solution are: *S1:* $n_{2\text{-}6} = 1$; $n_{3\text{-}5} = 1$; $n_{4\text{-}6} = 2$. *S2:* $n_{2\text{-}6} = 2$; $n_{3\text{-}5} = 1$; $n_{4\text{-}6} = 1$. *S3:* $n_{3\text{-}5} = 1$; $n_{4\text{-}6} = 3$. *S4:* $n_{2\text{-}6} = 3$; $n_{3\text{-}5} = 1$.

On the other hand, Table III shows the ISAs performance on the TEP problem for the Garver 6-bus system with dispatchable and non-dispatchable generation. For scenario *A_1*, the Algorithms (III-C-III-E) reach the best solution directly. The method with the best performance is the least-effort criterion varitant with a total TEP average time of 0.2006 s that is around 50-times faster than the traditional algorithm (10.0532 s), and 25-times than the percentage method (4.9379 s). Furthermore, the overload criterion reaches the best solution within 0.3644 s, almost 28-times faster than the traditional method and 14-times faster than the percentage method.

TABLE I
EXPANSION PLANS FOR GARVER 6-BUS SCENARIO *A_1* AND *A_2*

	Scenario	*A_1*				*A_2*
	Solution	*S1*	*S2*	*S3*	*S4*	
Path k-l	**Cost k-l**	**n**	**n**	**n**	**n**	**n**
2-6	30	1	2	-	3	3
3-5	20	1	1	1	1	1
4-6	30	2	1	3	-	2
Total new circuits		4	4	4	4	6
Total TEP [**US$**]		110	110	110	110	170
Unlimited reactives		Yes				Yes

For the following scenarios, the solution found (for each one) was attained by all algorithms (III-A-III-E).

2) Non-dispatchable generation: A non-dispatchable scenario is more complex than the dispatchable one; it means, the TEP problem is more difficult to be solved. Non-dispatchable scenarios have fixed generation and could simulate electric networks with 100% renewable energy penetration, such as photovoltaic, wind, and so on. Considering P_{Gi} as the active power generation at bus i (See [4, Appendix B.1]), the following fixed generation was set for this scenario:

$$P_{G3} = 165 \text{ MW}; \; P_{G6} = 545 \text{ MW}.$$

The best found solution for scenario *A_2* is shown in Table I and it agrees with the resulting topology found in [2]. This solution corresponds to an investment cost equal to $w =$ US$ 170, and the transmission circuits added to the base topology are: $n_{2\text{-}6} = 3$; $n_{3\text{-}5} = 1$; $n_{4\text{-}6} = 2$.

Table III scenario *A_2* shows that the backward method reaches the best solution directly in 9.7297 s. However, the overload criterion (Algorithm 2) shows the best performance with a total TEP average time of 0.3751 s; around 60-times faster than the traditional method (22.6307 s), and 35-times than the percentage method (13.1636 s).

TABLE II
EXPANSION PLAN FOR IEEE 24-BUS SCENARIO *B_1* AND *B_2*

	Scenario	*B_1*	*B_2*
Path k-l	**Cost k-l**	**n**	**n**
6-10	16	1	1
7-8	16	2	2
10-12	50	-	1
Total new circuits		4	6
Total TEP [**MUS$**]		48	98
Unlimited reactives		Yes	Yes

B. IEEE 24-bus system

It consists of 41 right-of-ways, a total load of 8550 MW and 1740 MVAr, and a total active power generation of 10215 MW. For both scenarios *B_1* and *B_2*, a population N of 60 individuals with a maximum of 200 iterations was considered; and, the number of trials was 10.

1) Dispatchable generation: Table II Scenario *B_1* shows the feasible solution, which agrees with the resulting plan found in [2]. The found solution corresponds to an investment cost equal to $w =$ MUS$ 48, and the transmission circuits added to the base topology are: $n_{6\text{-}10} = 1$; $n_{7\text{-}8} = 2$.

On the other hand, Table IV shows the ISAs performance on the TEP problem. For scenario *B_1*, the backward method reaches the least cost plan directly. The method with the best performance is the Overload Criterion with a total TEP average time of 18.7406 s. It is faster than the traditional algorithm (64.1723 s) and the percentage algorithm (21.9520 s).

2) Non-dispatchable generation: For this scenario, the slack node was changed from bus 1 to bus 13, setting the bus 1 as a PQ bus (See [4, Appendix B.2]). Additionally, the fixed generation was set up as follows:

$$P_{G1} = 576 \text{ MW}; \; P_{G2} = 576 \text{ MW}; \; P_{G7} = 900 \text{ MW};$$
$$P_{G15} = 325 \text{ MW}; P_{G16} = 282 \text{ MW}; P_{G18} = 603 \text{ MW};$$
$$P_{G21} = 951 \text{ MW}; P_{G22} = 900 \text{ MW}; P_{G23} = 1980 \text{ MW}.$$

The least cost plan found for Scenario *B_2* is shown in Table II. The best solution corresponds to an investment cost

TABLE III
GARVER 6-BUS SYSTEM WITH DISPATCHABLE AND NON-DISPATCHABLE GENERATION

	Garver 6-bus system with dispatchable generation *A_1*						Garver 6-bus system with non-dispatchable generation *A_2*					
Initial Solution Algorithm	*Traditional*	*Percentage*	*Least-Effort*	*Backward*	*Forward*	*Overload*	*Traditional*	*Percentage*	*Least-Effort*	*Backward*	*Forward*	*Overload*
Best initial [US$]	648	130	110	110	110	110	803	220	181	170	432	170
Worst initial [US$]	2206	307	110	110	110	110	2337	531	181	170	432	170
Average Best [US$]	803	201	110	110	110	110	887	321	181	170	432	170
Average LPSO iterations	21	11	-	-	-	-	46	28	32	-	26	-
Average ISA FE	-	-	12	991	61	23	-	-	12	961	136	23
Av. TEP and LPSO FE	1296	672	1	1	1	1	2787	1716	1926	1	1602	1
% Success	100	100	100	100	100	100	90	100	100	100	100	100
Average ISA time [s]	0.0033	0.1276	0.2005	9.8955	0.6127	0.3643	0.0038	0.1937	0.2277	9.7296	1.3401	0.3720
Average TEP time [s]	10.0532	4.9379	0.2006	9.8986	0.6128	0.3644	22.6307	13.1636	13.8360	9.7297	12.4694	0.3721

Population=60. Iterations=100. Trials=10. Percentage algorithm parameter: 10% for *A_1*, and 20% for *A_2*.
Average values consider the trials that reached the best solution only. The average of TEP and LPSO FE does not take into account the ISA FE.

TABLE IV
IEEE 24-BUS SYSTEM WITH DISPATCHABLE AND NON-DISPATCHABLE GENERATION

	IEEE 24-bus system with dispatchable generation *B_1*						IEEE 24-bus system with non-dispatchable generation *B_2*					
Initial Solution Algorithm	*Traditional*	*Percentage*	*Least-Effort*	*Backward*	*Forward*	*Overload*	*Traditional*	*Percentage*	*Least-Effort*	*Backward*	*Forward*	*Overload*
Best initial [MUS$]	2934	177	78	48	102	82	2980	260	134	98	116	132
Worst initial [MUS$]	3483	669	78	48	102	82	3506	1111	134	98	116	132
Average Best [MUS$]	3124	404	78	48	102	82	3188	833	134	98	116	132
Average LPSO iterations	79	30	26	-	25	25	95	42	35	-	41	36
Average ISA FE	-	-	43	6766	83	23	-	-	30	6725	124	23
Av. TEP and LPSO FE	4800	1814	1608	1	1560	1536	5760	2544	2142	1	2490	2196
% Success	80	90	100	100	90	100	90	100	100	100	100	100
Average ISA time (s)	0.0148	0.2644	1.4401	72.1372	1.0991	0.7164	0.0131	0.2567	1.0583	71.7924	1.5247	0.6748
Average TEP time (s)	64.1723	21.9520	20.0671	72.1416	19.7106	18.7406	74.6900	29.4585	26.7995	71.7926	30.2552	26.1090

Population=60. Iterations=200. Trials=10. Percentage algorithm parameter: 10% for *B_1* and *B_2*.
Average values consider the trials that reached the best solution only. The average of TEP and LPSO FE does not take into account the ISA FE.

equal to $w =$ MUS$ 98, and the transmission circuits added to the base topology are: $n_{6\text{-}10} = 1$; $n_{7\text{-}8} = 2$; $n_{10\text{-}12} = 1$.

For the Scenario *B_2*, Table IV shows that the backward method reaches the best solution directly with a computing time total of 71.7926 s. However, the Overload Criterion presents the best performance with a total TEP average time of 26.1090 s, around 3-times faster than the traditional algorithm (74.6900 s) and the percentage algorithm (29.4585 s).

V. CONCLUSIONS

The complexity in solving the TEP problem leads to find new algorithms aimed to solve the problem more efficiently. This work proposed random and deterministic algorithms for creating IS for the TEP problem. Results, obtained for the Garver 6-bus and IEEE 24-bus test systems, demonstrate the great impact that high-quality IS have on the TEP problem solution. For all scenarios, the backward method reaches the least cost solution directly; however, in some cases, the computing time was higher than the other algorithms due to the high value of maximum circuits per path adopted in this work. The proposed overload criterion represents a very robust alternative in creating IS for TEP, showing excellent performance for most dispatchable and non-dispatchable scenarios. Future work is undergoing to improve the performance of the algorithms, using larger electric networks.

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