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Optimal Allocation Renewable Energy Sources to Enhance Transient Stability of Active Distribution Networks

Mohammad Hossein Mehraban Jahromi*, Soodabeh Soleymani and Babak Mozafari

Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

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Abstract

Optimal allocating different rotational or inverter-based distributed generations (DGs) have facilitated the power systems' flexibility of operation. However, the deterioration of mechanical inertia due to allocating inverter-based DGs may threaten the dynamic security of the active distribution network. This study aims at transient stability preservation of the active distribution network. The transient stability preservation is accomplished based on the new objective function (OF) that maximizes the possible penetration level of the inverter based DG. The latter maximization result into the least deterioration of the transient stability margin. The proposed transient stability OF, relying on the critical clearing angle (CCA), is essentially an index being improved by taking into account both rotational and inverter based DGs. The procedure of calculating CCA is based on hybrid algorithm containing a sensitivity analysis together with some modifications on equal area criterion. The nature of CCA calculating procedure is so that the probable topology changes due to reconfigurations are also considered in the optimization problem. Photovoltaic panels, wind turbines, and electrical vehicles are investigated as the DGs. The IEEE 123-bus test system is adopted as the testbed to apply the proposed framework to. Further validation has been ensured considering several fault conditions.

Keywords: Transient Stability; Critical Clearing Angle; Optimization; Distributed Generation

1. Introduction

The conventional power plants are associated with a great deal of uncertainty from fuel costs and environmental related issues, which has resulted to a rapid increase of renewable energy sources (RESs) penetration in the electrical power system. Wind and solar type of energies are considered as the most accessible type of RESs for renewable generations. Recent studies on employing RESs in power grids [1] reveal that the enhancement of the RESs penetration level to over more than 20%–30% of the system's total generation, can cause their negative impacts on power grids to become unable to ignore. The significance of the latter negative effect can be impactful both in the static and dynamic security of the power system. Since the utilization of RESs as the distributed generations (DGs) is commonly in distribution networks, the impact of negative effects of RESs are very significant due to less strength comparing with a large interconnected power system. The main focus of this paper is on the optimal allocation of different technology of DGs in distribution networks considering minimum deterioration of the system's transient stability.

The optimization problem of optimally sizing and locating DGs has been extensively investigated in several publications. Most challenges in these research studies include the reduction of power loss, voltage profile improvement, voltage stability, reducing cost of operation, power quality and enhancement of reliability [2-5]. The optimization problem is investigated through different analytical, heuristic and Meta heuristic algorithms [6-8]. However, surveying literatures reveals that the majority of publications in optimal allocation of DGs have concentrated on the static aspects distribution networks.

Transient stability or large disturbance rotor angle stability problem is one of the most challenging issues in dynamic security assessment of the power grids. Conventionally, transient stability has been investigated in the transmission grid concentrating on the large synchronous power plants. However, high penetration of RESs in distribution networks, transient stability analysis has become important in active distribution network.

Literature surveying regarding transient stability analysis in distribution network indicate that transient stability analysis have mainly focused on the impact of various rotational type DGs such as synchronous DG types [9-11], and induction-based DG [12-14] and also the contribution of Plug-in Electrical Vehicle (PEV) and Photovoltaic (PV) [15-18] in transient stability condition though time domain simulation analysis.

It is to note that several investigations regarding the impact of PV and PEV on frequency stability [19-21] indicate the significant role of inverter-based DGs on the grid stability condition. Such studies have tried to put forward the effects PVs and PEVs can lay, by taking into consideration the power electronic devices [18, 21], not to be only included into the calculations as negative loadings [22]. It is worth noting that most of previous publications have conducted research studies on finding the frequency control to ensure less deterioration of grid frequency due to side effect of inverter-based DGs on frequency stability [23, 24].

Surveying the literature for DG optimal allocation in distribution networks, the transient stability margin enhancement issue has been discussed for DG-integrated

*E-mail address: mh.mehraban@srbiau.ac.ir
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distribution networks only by the authors in [25]. The authors in [26], have introduced a critical-clearing-time-maximization-based objective function, considering micro turbine DG type . However, throughout the literature, the optimal allocation of simultaneously rotational and inverter-based DGs to ensure transient stability preservation has not yet been put forward.

This study tries to lay out the transient stability preservation of distribution networks with optimally allocation of different rotational and inverter-based type of DGs. The focus of the paper is providing of an optimization based framework that accurately considers the transient stability constrains of the distribution network comprising with the different rotational and inverter-based type of DGs. This paper has the following contributions:

- This paper considers two inverter-based type DGs consisting of photovoltaic and electrical vehicles, and induction generator wind turbine type of DG. To unify transient stability analysis framework, the mathematical model inverter-based type of DGs for transient stability is derived with the help of virtual synchronous generator concept. As it is to be shown in the problem statement, the model which is extracted leads to simplicity in understanding and implementing of the proposed method.
- The proposed objective function for transient stability is principally based on the corrected critical clearing angle (CCCA). To construct objective function, this paper proposes new unique framework in which CCCA of both rotational and non-rotational DGs are calculated. To calculate CCCA, equal area criterion (EAC) is used for extracted CCA for both rotational and non-rotational DGs. After that, utilizing sensitivity analysis, CKE is corrected to take the fault trajectory effect into account.
- The proposed procedure of calculation of CCA is provided with a sensitivity analysis to deal with probable topology changes due to distribution network reconfigurations and contingencies. Through the latter sensitivity analysis, the immunity of the proposed OF is also enhanced for both grid-connected and islanding operation of active distribution grids.

2. Proposed Framework for Transient Stability

Transient stability has conventionally discussed the ability of preserving synchronism between synchronous generators as a severe disturbance is imposed to the power system [27]. Several information regarding system operating condition in pre-disturbance conditions, fault location, fault type, and fault duration are required for performing transient stability analysis.

As the penetrations of RESs increased, rotational generator units have been replaced by inverter-based interface generator units. Such a replacement is associated with several advantages in the operation of power systems, however, it has also weakened the mechanical inertia, leading to deterioration of the power system to instability [28].

This paper tries to optimally distribute different rotational and non-rotational types of DGs to preserve the margin of transient stability in distribution networks. To such aim, first proper mathematical modeling of DGs such as electrical vehicles and photovoltaic panels, and induction generator wind turbine are discussed. Thereafter, the CCA calculation problem for each individual generator is dealt with through introduction and development of a mathematical basis. Ultimately, the condition of transient stability is enhanced through introduction of an objective function being discussed further on.

2.1. Transient Stability Mathematical Modeling for Inverter-Based DGs

During disturbances, it is important to keep inverter based DGs synchronize with power grid. Increasing inverter-based DGs in distribution network has challenges in preserving instability since it may have inability to injection of balancing energy in proper time interval. The concept of virtual synchronous generator (VSG) is widely utilized to control the inverter-based DGs so that it seems each DG is emulating real synchronous generator.

In this paper, the concept of VSG is utilized to model PV and PEV using dynamic mathematical equations as follows [28]:

$$\dot{\delta}_{VSG,i} = \omega_0(\omega_{VSG,i} - 1) \tag{1}$$

$$\tau_{VSG,i}\dot{\omega}_{VSG,i} = P_{m,i} - P_{VSG,i} - J_{p,i}(\omega_{VSG,i} - 1) \tag{2}$$

$$\tau_{K,i}\dot{E}'_{VSG,i} = Q_{m,i} - Q_{VSG,i} - J_{q,i}(V_{PCC,i} - 1) \tag{3}$$

$$P_{VSG,i} = \frac{E'_{VSG,i}V_{PCC,i}}{X'_{f,i}}\sin\delta_{VSG,i} \tag{4}$$

$$Q_{VSG,i} = \frac{E'^2_{VSG,i} - E'_{VSG,i}V_{PCC,i}\cos\delta_{VSG,i}}{X'_{f,i}} \tag{5}$$

It is worth noting that $\delta_{VSG,i}$, $\omega_{VSG,i}$, $P_{m,i}$, $P_{VSG,i}$, $Q_{m,i}$, $Q_{VSG,i}$, $E'_{VSG,i}$, and $V_{PCC,i}$ are in per-unit.

2.2. Transient Stability Mathematical Modeling for Wind Turbine Generator

For wind energy application, three types of generators are commonly used including Induction Generators (IG), Doubly-Fed Induction Generators (DFIG), and Permanent Magnet Generators (PMG). Among these generators, DFIG has become most famous type of wind turbine generators that is used for variable-speed wind applications. For transient stability analysis, dynamic mathematical equations are as follows [28]:

$$\dot{\delta}_{dfig,i} = \omega_{dfig,i} - \omega_0 - \frac{X_{s,i} - X'_{s,i}}{X'_{s,i}}\frac{V_{PCC,i}\sin(\delta_{dfig,i} - \theta_{PCC,i})}{\tau_{dfig,i}E'_{dfig,i}} + \frac{\omega_0 V_{dfig,r,i}\sin(\delta_{dfig,i} - \theta_{dfig,r,i})}{E'_{dfig,i}} \tag{6}$$

$$\dot{\omega}_{dfig,i} = \frac{\omega_0}{J_{dfig,i}}(P_{m,i} - P_{dfig,i}) \tag{7}$$

$$\dot{E}'_{dfig,i} = -\frac{X_{s,i}E'_{dfig,i}}{\tau_{dfig,i}X'_{s,i}} + \frac{X_{s,i} - X'_{s,i}}{\tau_{dfig,i}X'_{s,i}}V_{PCC,i}\sin(\delta_{dfig,i} - \theta_{PCC,i}) + \omega_0 V_{dfig,r,i}\sin(\delta_{dfig,i} - \theta_{dfig,r,i}) \tag{8}$$

$$P_{dfig,i} = \frac{E'_{dfig,i}V_{PCC,i}}{X'_{s,i}}\sin(\delta_{dfig,i} - \theta_{PCC,i}) \tag{9}$$

where

$$\tau_{dfig,i} = \frac{L_{rr,dfig,i}}{R_{r,dfig,i}} \text{ and } X'_{s,i} = \omega_0 (L_{ss,dfig,i} - \frac{L^2_{m,dfig,i}}{L_{rr,dfig,i}}) \quad (10)$$

2.3. Calculation of Corrected Critical Clearing Angle

As previously mentioned, the basis of the proposed objective function is laid on the CCCA. This section tries to find CCCA for each generator in three stages:

(1) Calculating initial guess of CCA based on Equal Area Criterion (EAC),
(2) Correction of CCA to consider through a sensitivity analysis probable topology changes to consider network reconfigurations, network islanding, and contingencies
(3) Correcting CCA through a sensitivity analysis taking the effect of fault trajectory into consideration, and calculating CCCA.

In the following, the three stages are comprehensively described.

2.3.1. Calculation of Critical Clearing Angle

Traditionally, transient stability assessment of an individual generator was conducted based on the EAC approach.
To calculate CCCA, first an initial guess for CCA is calculated based on the concept of single machine to infinite bus. As it can be seen in Figure 1, each DG is assumed to be connected to a virtual machine, characterizing an infinite bus (Inf. Bus). The significance of the two-bus system considered in this study with respect to the conventional EAC [26, 29] is that the power is delivered to the system from the considered generator bus at the transient voltage of (E'_{DG}) through the reactance (X'_{DG}). With such a consideration assumed, the problem is highly simplified and the dependency to the parameters of system (i.e. line parameters pre/mid/post -fault) is avoided. Nevertheless, the modeling approach of an infinite bus assumption is associated with inaccuracy to some extent. Particularly, the voltage $V_{PCC}\measuredangle\theta_{PCC}$ is assumed equal to $1\measuredangle 0^{\circ}$ for the sake of the aforementioned approach. Such inaccuracies are corrected by the technique discussed in the following section.

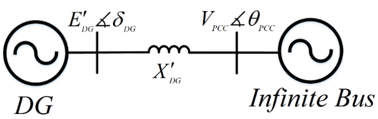


Fig. 1. Finding CCA employing the EAC concept.

CCA is defined as the critical clearing angle, for a three-phase to ground fault at the DG terminal. During such severe fault, DG electrical output power $P_{DG,i}$ becomes almost zero while the input mechanical power ($P_{m,i}$) stays nearly constant in transient stability studies [26]. For such a fault scenario, EAC for calculating CCA is represented in Figure 2. As it is illustrated in Figure 3, after fault inception in δ_0, rotor of the generator accelerates meaning that the angle-power operating point is shifted from point (a) to point (e) during the mid-fault time. Subsequent to fault clearance in δ_c, because of the de-acceleration of rotor, the kinetic energy absorbed by rotor converts to potential energy until there is zero kinetic energy imaginable in the generator, pushing the operating point into point (f).

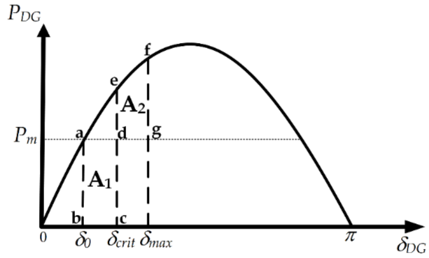


Fig. 2. EAC concept calculating CCA

Mathematical description of Figure 2 is as follows:

$$\int_{\delta_{0,i}}^{\delta_{c,i}} P_{m,i} d\delta_{DG,i} = \int_{\delta_{c,i}}^{\delta_{\max,i}} (P_{DG,i} - P_{m,i}) d\delta_{DG,i} \quad (11)$$

By calculation of (11), the following is obtained:

$$P_{m,i}(\delta_{c,i} - \delta_{0,i}) = \frac{E'_{DG,i} V_{PCC,i}}{X'_{DG,i}} \left(\cos(\delta_{\max,i} - \theta_{PCC,i}) - \cos(\delta_{c,i} - \theta_{PCC,i}) \right) - P_{m,i}(\delta_{\max,i} - \delta_{c,i}) \quad (12)$$

As for the initial guess in calculation of (12), $\delta_{\max,i}$ is assumed $\pi - \delta_{0,i}$. Accordingly, some simplifications can be applied on (12), and the clearing angle is calculated as follows:

$$\delta_{c,i} = \cos^{-1}\left(\cos(\pi - \delta_{0,i} - \theta_{PCC,i}) + \frac{X'_{f,i} P_{m,i}}{E'_{VSG,i} V_{PCC,i}} (2\delta_{0,i} - \pi) \right) + \theta_{PCC,i} \quad (13)$$

Considering $V_{PCC}\measuredangle\theta_{PCC}$ is equal to $1\measuredangle 0^{\circ}$, equation (13) is obtained as follows:

$$\delta_{c,i} = \cos^{-1}\left(\cos(\pi - \delta_{0,i}) + \frac{X'_{f,i} P_{m,i}}{E'_{VSG,i}} (2\delta_{0,i} - \pi) \right) \quad (14)$$

2.3.2. Correction of CCA for Infinite Bus and Topology Changes

In the last section, to simplify the calculation, $V_{PCC}\measuredangle\theta_{PCC}$ was assumed equal to $1\measuredangle 0^{\circ}$. However, such an assumption is not necessarily correct, for two possible reasons: first during optimization procedure, the location of DG changes and in each bus $V_{PCC}\measuredangle\theta_{PCC}$ has different value. Second, distribution network may confront reconfiguration, contingencies and it may also operate in scheduled or unscheduled islanding mode which impose variations in the PCC's voltage. The value of $V_{PCC}\measuredangle\theta_{PCC}$ varies. To reflect the variations of PCC's voltage on the calculation, using corrected $V_{PCC}\measuredangle\theta_{PCC}$, CCA is corrected as follows:

$$\begin{aligned}
CCA_i &= CCA_{i,0} + \frac{\partial CCA_i}{\partial V_{PCC,i}} + \frac{\partial CCA_i}{\partial \theta_{PCC,i}} \\
&= CCA_{i,0} + \frac{\dfrac{X'_{DG,i} P_{m,i}}{E'_{DG,i} V^2_{PCC,i}}}{\sqrt{1 - \left(\cos(\pi - \delta_{0,i} - \theta_{PCC,i}) + \dfrac{X'_{DG,i} P_{m,i}}{E'_{DG,i} V_{PCC,i}} (2\delta_{0,i} - \pi) \right)^2}} \\
&\quad - \frac{\sin(\pi - \delta_{0,i} - \theta_{PCC,i})}{\sqrt{1 - \left(\cos(\pi - \delta_{0,i} - \theta_{PCC,i}) + \dfrac{X'_{DG,i} P_{m,i}}{E'_{DG,i} V_{PCC,i}} (2\delta_{0,i} - \pi) \right)^2}} + 1
\end{aligned} \quad (15)$$

It is important to note that the parameters $E'_{DG,i}$, $X'_{DG,i}$, $P_{m,i}$ and $\delta_{0,i}$ in equation (15), are obtained from the pre-fault condition. Hence, it is possible to calculate the CCA_0 for each DG, and to utilize the obtained points for initialization. The optimization problem is conducted for every random set of locations, and the $V_{PCC}\measuredangle\theta_{PCC}$ value is varied accordingly, updating the CCA by (15).

It is worth noting that for the fault trajectory effect to be taken into consideration, the CCA is also necessary to be corrected regarding each location of fault, subsequent to the corrections made through the aforementioned procedure.

2.3.3. CCA Correction for Fault Location

The CCA calculation is mainly carried out for the near-generator faults. However, as for the fault locations being inherently variable, in the CCA value can significantly change. On this ground, the effect of fault trajectory is necessary to be taken into account. To such end, the CCCA is proposed to be calculated as follows:

$$CCCA_i = CCA_i + \frac{\partial CCA_i}{\partial S_i} \tag{16}$$

Where S_i is an interim variable depending on the location of fault. Based on (16), it is clearly deduced that $E'_{DG,i}$ and $V_{PCC,i}$ differ as the fault location varies. Therefore, the CCA_i sensitivity to the location of fault is obtained as:

$$\begin{aligned}\frac{\partial CCA_i}{\partial S_i} &= \frac{\partial CCA_i}{\partial E'_{DG,i}} + \frac{\partial CCA_i}{\partial V_{PCC,i}} \\ &= \frac{\dfrac{X'_{DG,i}P_{m,i}}{V_{PCC,i}E'^2_{DG,i}}}{\sqrt{1-\left(\cos(\pi-\delta_{0,i})+\dfrac{X'_{DG,i}P_{m,i}}{E'_{DG,i}V_{PCC,i}}(2\delta_{0,i}-\pi)\right)^2}} \\ &+ \frac{\dfrac{X'_{DG,i}P_{m,i}}{E'_{DG,i}V^2_{PCC,i}}}{\sqrt{1-\left(\cos(\pi-\delta_{0,i})+\dfrac{X'_{DG,i}P_{m,i}}{E'_{DG,i}V_{PCC,i}}(2\delta_{0,i}-\pi)\right)^2}}\end{aligned} \tag{17}$$

According to (17), CCCA is calculated as follows:

$$\begin{aligned}CCCA_i &= CCA_i + \frac{\partial CCA_i}{\partial S_i} \\ &= CCA_i + \frac{X'_{DG,i}P_{m,i}\left(\dfrac{1}{V_{PCC,i}}+\dfrac{1}{E'_{DG,i}}\right)}{(V_{PCC,i}\times E'_{DG,i})\sqrt{1-\left(\cos(\pi-\delta_{0,i})+\dfrac{X'_{DG,i}P_{m,i}}{E'_{DG,i}V_{PCC,i}}(2\delta_{0,i}-\pi)\right)^2}}\end{aligned} \tag{18}$$

3. Implementation

The following section presents an explanatory portion to define the OFs and their corresponding constrains for the solution of the optimization problem.

3.1. Proposed Objective Function for Preserving Transient Stability

The proposed transient stability OF for taking into consideration the dynamic behavior of inverter based and rotational DGs is defined as follows:

$$G_1 = \frac{\sum_{n=1}^{N_b}\sum_{g=1}^{N_g} FP_n J_g CCA_{gn}}{\sum_{n=1}^{N_b}\sum_{g=1}^{N_g} FP_n J_g} \tag{19}$$

$$G_2 = \frac{\sum_{n=1}^{N_b}\sum_{g=1}^{N_g} FP_n J_g CCCA_{gn}}{\sum_{n=1}^{N_b}\sum_{g=1}^{N_g} FP_n J_g} \tag{20}$$

$$h_1 = \left|\frac{G_2 - G_1}{G_2 + G_1}\right| \tag{21}$$

$$OF_1 = Minmization\ \{h_1\} \tag{22}$$

Where G_1 and G_2 are two interim functions. Minimization of OF_1 will lead to have maximum withstanding ability during transient stability. To construct h_1, the effects laid by the DG's inertia (J) and the fault probability (PF) are considered for each bus.

3.2. Voltage regulation and Network Loss OFs

To improve the voltage profile and reduction of power losses, the following OFs are also considered for preservation of the distribution networks' steady state operation as follows:

$$\begin{aligned}h_2 &= P_{L,p.u}^{Lines} + P_{L,p.u}^{Transformers} \\ OF_2 &= Minmization\ \{h_2\}\end{aligned} \tag{23}$$

$$\begin{aligned}h_3 &= \sum_{n=1}^{N_b}(V_{n,p.u}-1)^2 \\ OF_3 &= Minmization\ \{h_3\}\end{aligned} \tag{24}$$

It is noteworthy that the steady state OFs are presented in order to better demonstrate the necessity to consider transient stability OFs alongside the steady state OFs.

3.3. Constrains

The OFs are solved considering the constrains in the Table1:

Table1. Objective function constrains

Voltage Limitation	$0.95 \le V_n^{p.u} \le 1$
Limitation of DG Output	$P_{e,\min} \le P_{e,i} \le P_{e,\max}$
Line Flow Limitation	$S_l \le \lvert S_{l,\max}\rvert$

4. Simulation results and discussion

This section is provided to validate the efficiency of the proposed algorithm. IEEE 123-bus distribution network is chosen as the testbed system at voltage level 115/4.16 kV with total 16 MW commercial and residential loads [31].

The verification of the effectiveness of the OF is investigated with/without the impact of static OFs (2) to (4). During solving optimization problem, specifications given in Table 2 are taken into consideration.

Table 2. Specifications of the number and size of DGs during solving optimization problem

	IEEE 123-bus	
	Min	**Max**
Total Number of DGs	6	9
Size of PV	1 MW	4 MW
Size of PEV	0.5MW	2 MW
Size of WT	3 MW	7 MW

Once the allocation of the DGs is performed with/without proposed transient stability OF, the ability of transient stability enhancement is essential to demonstrate. In [29], the authors have suggested a transient stability index (TSI) in which can evaluate the transient stability condition for the whole system based on the critical kinetic energy [29]. TSI is an index that varies between (0,1) and the TSI close to zero means that the transient stability of the system is ensured and vice versa. In this paper TSI is utilized to evaluate the transient stability margin of distribution network before/after DG allocation. During generating of fault scenarios for calculating TSI, fault duration is assumed a uniform probability distribution function that varies between 120 to 150 ms. Also the fault type is assumed three phase fault to ground.

In this paper, the OFs will be solved with four optimization algorithms such as Particle Swarm Optimization (PSO) Algorithm [32], Gravitational Search Algorithm (GSA) Algorithm [33], Ant Colony Optimization (ACO) Algorithm [33], and Artificial Bee Colony (ABC) Algorithm [33]. The parameters of these algorithms are specified according to Table 3.

Table 3. The Characteristics of Optimization Methods

Algorithm	**Number of Population**	**Number of Iteration**	**Dimensions**	**Stopping Time Limit (Se)**
PSO	20	180	55	inf
GSA	20	180	55	inf
ACO	20	180	55	inf
ABC	20	180	55	inf

4.1. Optimal Allocation based on the transient stability OF

This section is allocated to investigating the performance of performance of the transient stability OF to find optimal size and location of the RESs including WT, PV and PEV. Applying optimization problem on IEEE 123-bus, the results of the four optimization algorithms are given in Table 4. While all results given in Table 4 are optimal solution for different total number of DGs, case 2 have minimum value of OF comparing with the other cases. To verify the result of optimization, TSI is calculated for fault at all of the buses. The results of TSI for all cases are shown in Figure 3.

Table 4. The numerical outputs of optimization algorithms for employment of the proposed OF on IEEE 123-bus

Case	**Total Number of DGs**	**WT**	**PV**	**PEV**	**OF(p.u)**			
		Location @ Size	**Location @ Size**	**Location @ Size**	**PSO**	**GSA**	**ACO**	**ABC**
1	6	34@ 5.44 69@ 1.97	83@ 3.54 39@ 2.97 27@ 5.91	62@ 1.29	0.578	0.714	0.489	0.318
2	7	26@ 6.14 49@ 5.84 96@ 4.83	21@ 1.29 85@ 2.1	74@ 0.78 13@ 0.62	0.078	0.043	0.019	0.034
3	8	29@ 4.16 62@ 5.94 57@ 4.25	6@ 2.16 10@ 1.34 13@ 2.25	19@ 0.79 27@ 1.28	0.093	0.167	0.12	0.058
4	9	53@ 4.79 47@ 2.31	23@ 4.41 77@ 3.91 106@ 2.41 48@ 3.71	67@ 1.4 59@ 1.31 27@ 0.84	0.746	0.522	0.384	0.794

As illustrated in Figure 3, different number and size of the DGs allocation has provided different strength and margin of transient stability for the test system. Comparing all cases, it can be observed that while in all cases the value of TSI does not exceed from 0.5, case 2 provides overall minimum TSI for fault at all buses. This means the combinations of DGs in number, size and location has improved transient stability margin of the test system more than other cases.

One important observation from Figure 3 is that increasing the total size of inverter based sources even during an optimization process does not guarantee the increasing the withstanding of the distribution network during transient stability. As it can be seen in Table 4, the total size of PV and PEV in case 4 is more than WT, while this issue is contrariwise for case 2. This result reveals that there is a certain penetration level for inverter based sources that should not be violated.

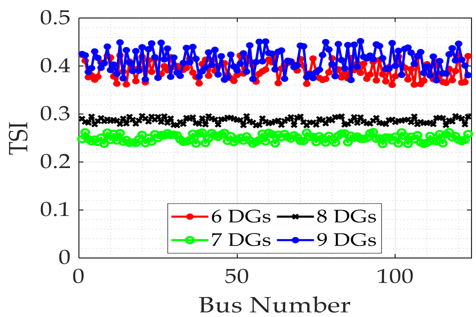


Fig. 3. TSI after DG allocation only considering transient stability OF

It is important to find the effectiveness of the proposed OF for transient stability during non-optimal solutions. Such investigation is conducted based on the randomly produced location with same number and size similar to each case of the Table 5. As it can be seen in Figure 4, regardless the number of RESs, the TSI for non-optimal solution has notable difference with optimal solution. As it can be seen in Figure 4, the TSI varies between 0.6 to 0.8, which means that the distribution network has very less robustness during transient stability comparing with TSI of optimal solution.

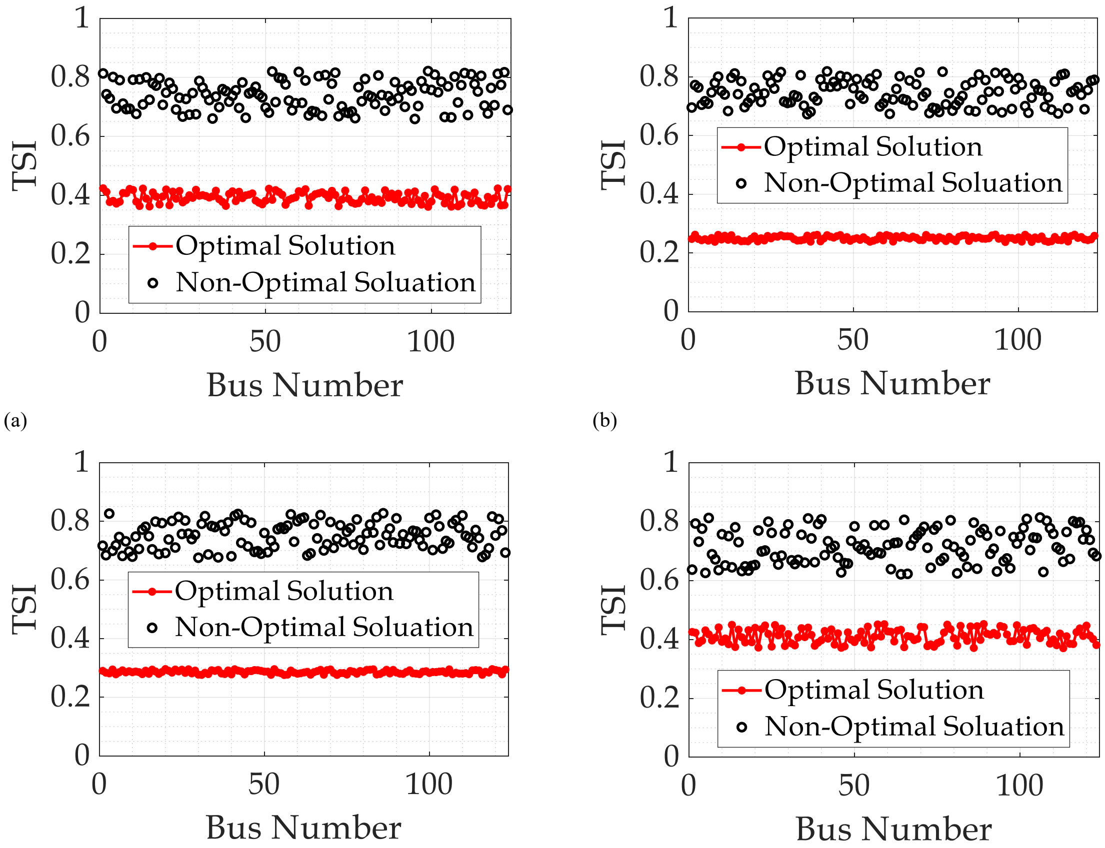
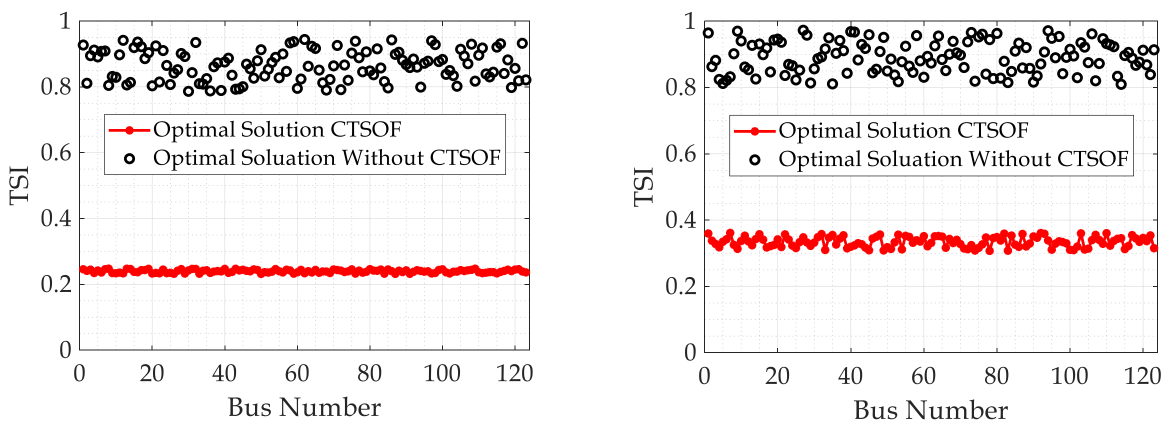


Fig. 4. TSI of the IEEE 123-bus test system under optimal and non-optimal DG allocation only taking the transient stability OF into consideration (a) 6 DGs, (b) 7 DGs, (c) 8 DGs, and (d) 9 DGs

4.2. Allocation of DGs Considering All Dynamic and Static OFs

This section is dedicated to optimal allocation of DGs with/without proposed transient stability OF considered. In this investigation, the impact of different reconfigurations along with OFs 2 to 4 is considered. The results are only provided for total number 7 and 8 DGs in the test system. The optimal allocations are conducted taking all objective functions into consideration with equal weighting factors.

As it can be seen in Figure 5, without considering transient stability OF (CTSOF) in allocation of DGs, TSI values are very close to 1 which indicates the system is very vulnerable during transient stability.



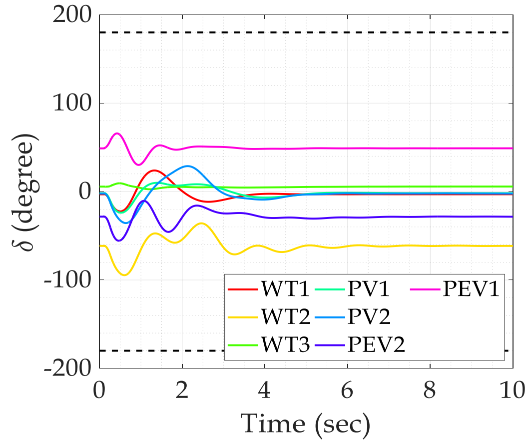
(a) (b)

Fig. 5. Investigation the impact of considering all dynamic and static OFs (a) 7 DGs, (b) 8 DGs

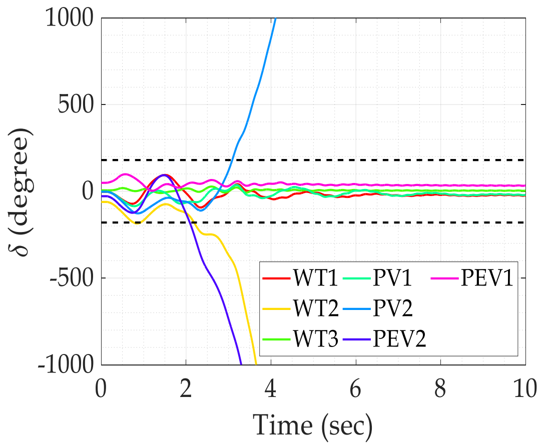
For the sake of a more appropriate illustration concerning the effectiveness of the proposed OF for transient stability, the rotor angles corresponding to the DGs for scenarios presented in Table 5 are demonstrated in the Figure 6. According to the results, the optimal DG allocation employing the proposed OF for transient stability ensured the transient stability of the DGs, as depicted in Figures 6.a and c, showing the rotor angles corresponding to DGs. Even though, the rotor angles in Figures 6.b and d, get unstable due to lack of CTSOF.

Table 5. time domain simulation scenarios of fault for evaluation of optimal allocation with/without CTSOF in case of allocating 7 DGs

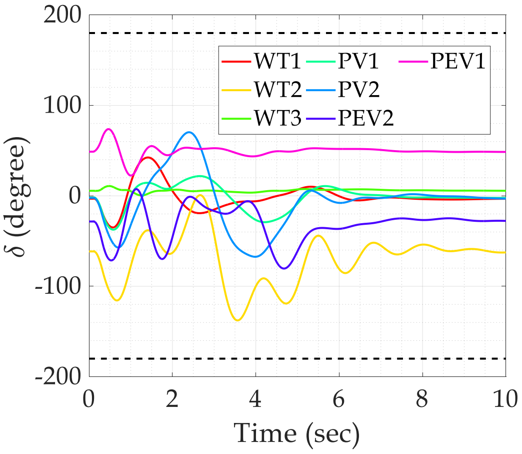
Scenarios	**Description**	**Fault Location (Bus)**	**Fault duration (ms)**
Scenario 1	CTSOF	56	125
Scenario 2	Without CTSOF		
Scenario 3	CTSOF	75	150
Scenario 4	Without CTSOF		



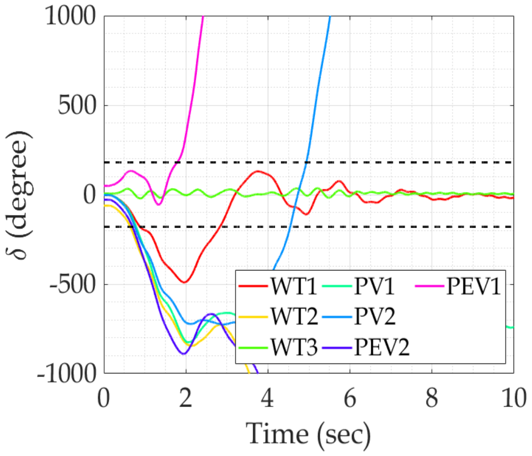
(a)



(b)



(c)



(d)

Fig. 6. Rotor angles for optimal allocation of 7 DGs with/without transient stability OF considered (a) Scenario 1 in Table 5, (b) Scenario 2 in Table 5, (c) Scenario 3 in Table 5, and (d) Scenario 4 in Table 5.

4.3. Comparison with the State-of-the-Art and Discussion

As alluded in the introduction, an OF is proposed in [14] taking the transient stability into account for DG allocation. In this section, optimal allocation has been carried out by the proposed method (M1) and the method suggested in [14] (M2), and the results of which are put into comparison afterwards. Such a comparison is conducted, only considering the transient stability OFs under different reconfigurations, assuming the total number of DGs equal to 7. The results from DG optimal allocation employing both methods are tabulated in Table 6.

Table 6. Comparison with the State-of-the-Art

Case	**Method**	**WT**	**PV**	**PEV**	**OF(p.u)**			
		Location @ Size	**Location @ Size**	**Location @ Size**	**PSO**	**GSA**	**ACO**	**ABC**
1	M1	26@6.14 49@5.84 96@4.83	21@1.29 85@3.1	74@0.78 13@1.62	0.078	0.043	0.019	0.034
2	M2	26@4.16 10@3.39	6@3.61 90@4.34 113@5.25	19@1.79 47@1.28	0.193	0.267	0.172	0.538

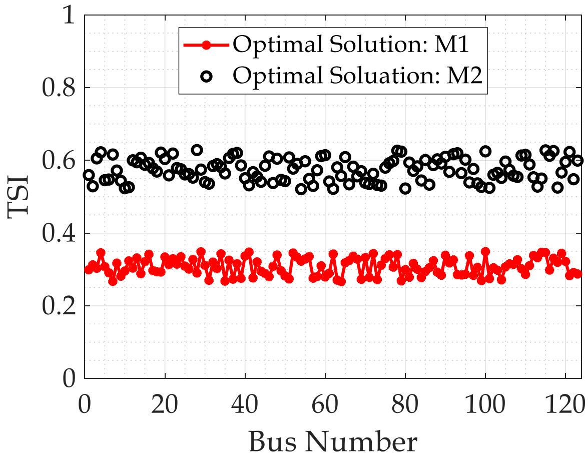


Fig. 7. Comparison between the performances of the proposed OF and [14].

As depicted in Figure 7, the TSI from the proposed approach presents a higher ability to preserve the transient stability in comparison to the method in [14]. Taking the PEI of DGs through VSG into account, selecting an appropriate mathematical model of different rotational and inverter-based DGs for unifying transient stability analysis, and considering different reconfigurations into the DG optimal allocation problem, are the factors that cause the proposed method to show a better performance with respect to the method in [14].

4.4. Performance of Optimization Algorithms from Computational Time Aspect

In the previous subsections, the performance of the proposed transient stability OF was investigated under various conditions. This subsection provides performance comparison between optimization algorithms from computational time (C.T) aspect. The C.T of the optimization algorithms which is based on second, are tabulated in Table 7.

Table 7. Performance of Optimization Algorithms from Computational Time Aspect

Subsections	Condition	PSO	GSA	ACO	ABC
4-1	Case 1	1215.4	1392.4	901.3	1412.5
	Case 2	1216.8	1388.6	870	1434.3
	Case 3	1312	1339.4	979	1340.7
	Case 4	1240.4	1341.1	949.5	1401.1
4-2	Case 1	3569.6	3696.3	2066.4	3698.7
	Case 2	3513.3	3730	2107.2	3636.9
4-3	Case 1	2227.4	2493.6	1751.9	2365.3
	Case 2	10265.1	10440.3	9932.1	10449.6

As it can be seen in Table7, ACO algorithm has the lowest C.T values among all cases. In subsection 4.2, since all OFs are taken into account, the C.Ts is greater than subsections 4.1. Also, in cases of subsections 4-3, the C.T times are very high comparing with subsections 4.1, since multiple reconfigurations are considered in the process of optimization. One important point is that in case 1 (i.e. proposed method) since a recursive algorithm is employed in the proposed algorithm, the C.T time is notably low comparing with case 2 (i.e. [14]).

5. Conclusion

High penetration of inverter-based RESs may threaten the preservation of the transient stability in the active distribution networks as a result of diminishing in the system's mechanical inertia. In this paper, a new OF was introduced which has been designed to properly allocate different rotational and inverter-based DGs in distribution network so that the withstanding ability during transient stability of the grid is preserved. The proposed OF is based on the CCCA and it is constructed based on the concept of virtual synchronous generator. This paper is mainly focused on the unification of WT, PV and PEV into one mathematical framework so that the transient stability analysis less complicated. Applying proposed method on the standard IEEE 123-bus test system, the proposed method was evaluated and compared with different method in various conditions. The achievements are described as follows:

- The proposed approach is capable to optimally allocate WT, PV and PEV to find maximum transient stability withstanding ability. Optimal allocation of DGs with different number, size and location indicate as the level of penetration increases, the margin of transient stability is decreased.
- Randomly distribution of DGs with optimal number and size of DGs will lead to less strength during transient stability.
- Optimal DG allocation without considering transient stability OF will lead to maximum vulnerability against transient stability.
- The proposed method has more preserving ability during transient stability in comparison to the state-of-the-art. The latter supremacy of the proposed method is resulted due to taking the PEI of DGs through VSG into account, choosing an appropriate mathematical model of different rotational and inverter-based DGs for unifying transient stability analysis, and considering different reconfigurations into optimal allocation of DGs.
- Concentrating on the computational time of optimization algorithms, it was demonstrated that between the optimization algorithms ACO has the lowest C.T in all cases. Also comparing with the state-of-the-art, the C.T of the proposed method is very low since the proposed method utilizes recursive calculation into proposed algorithm.

Based on the achievement, the proposed method can properly deal with allocation of different type DGs considering preserving the power system transient stability at the planning stage. Further work can be expanded on the controlling frequency and voltage stability strategies.

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Nomenclature

Following parameters, acronyms and abbreviations have been used in this paper:

DG	distributed generation	ω_{VSG}	the virtual angular speed
RES	renewable energy source	ω_0	the nominal angular speed
PCC	point of common coupling	P_m	Mechanical active power
PV	Photovoltaic	P_{VSG}	VSG output active power
PEV	Plug-in Electrical Vehicle	Q_m	reactive power reference
EAC	equal area criterion	Q_{VSG}	VSG output reactive power
CCA	Critical Clearing Angle	E'_{VSG}	RMS value of internal potential
CCCA	Corrected Critical Clearing Angle	V_{PCC}	PCC RMS voltage
VSG	virtual synchronous generator	X'_f	Filter Impedance
PSO	Particle Swarm Optimization	τ_{VSG}	time constant of VSG
GSA	Gravitational Search Algorithm	J_p	VSG damping coefficient
ACO	Ant Colony Optimization	$\tau_{K,i}$	time constant corresponding to reactive power loop
ABC	Artificial Bee Colony	J_q	Damping coefficient corresponding to voltage control loop
CKE	Corrected Kinetic Energy	δ_0	Pre-fault operating point
LCS	Large Change Sensitivity	δ_c	Critical clearing point
δ_{VSG}	internal voltage phase angle	$\delta_{\max}$	After fault operating point