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Allocating Different Types of Distributed Generations Concentrating on Transient Stability Enhancement in Distribution Network

Mohsen Tajdinian
Distribution Grid Designer and R&D Researcher, Moheb Niroo Consultant Engineering, Shiraz, Iran; Department of Power and Control Engineering, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran
tajdinian.m@shirazu.ac.ir

Reza Shirali
Director of Designing & Supervision Department, Moheb Niroo Consultant Engineering, Shiraz, Iran
m.shirali@shirazu.ac.ir

Behzad Behdani
Department of Power and Control Engineering, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran
b.behdani@shirazu.ac.ir

Mojtaba Abbasi
Board Member and Chairman, Moheb Niroo Consultant Engineering Company, Shiraz, Iran
abbasi1230@yahoo.com, abbasi@mohebniroo.com

Harold R. Chamorro
Department of Electrical Engineering, KTH, Royal Institute of Technology, Stockholm, Sweden
hr.chamo@ieee.org

***Abstract*—Proliferation of renewable energy sources (RESs) has increased the reliability and flexibility in the operation of the power networks. Nevertheless, different technologies of RESs with different sizes and grid-connection technologies may impose threats to the power grid's stability. This paper targets transient stability in distribution networks. More specifically, this paper investigates the allocation of different types of distributed generations (DGs) considering the maximization of transient stability margin. The latter maximization helps to minimize the deterioration of the inverter-based DGs. The transient stability based objective function (OF) basically relies on the critical and clearing angles. Besides transient stability, the improvement of voltage profile and minimization of power losses are taken into account. The proposed algorithm is implemented on the IEEE 33-bus test system and furthermore, several scenarios are conducted to ensure the effectiveness of the proposed algorithm under fault conditions.**

Keywords—Distributed Generation, Optimal Allocation, Photovoltaic, Renewable Energy Sources, Transient Stability.

I. Introduction

By increasing the environmental and fuel cost issues of the conventional power plants, employing renewable energy sources (RESs) in the electrical power system has rapidly increased [1]. Among the accessible types of RESs, wind [2] and solar [3] energies are the most famous renewables. Research studies on the impacts RESs in power grids [1] unfold that the RESs can impose negative impacts on the power grids as the penetration level exceeds more than 20%–30% of the system's total generation. Such negative impacts threaten the static and dynamic security of the system. Also, the RESs are commonly used as the distributed generations (DGs) in distribution grids, and these negative impacts can be more severe compared to a large transmission system. This paper focuses on the optimal placement of DGs in distribution grids targeting the transient stability enhancement of the grids.

Several researches have worked on the optimal solution for DG allocation in distribution networks from different aspects. Most of these studies have addressed distribution grid challenges, e.g., improving voltage profile, voltage stability, reliability, power quality, and reduction of power losses and operation costs [4]-[7]. It is worth noting that the optimal solutions are obtained via different approaches including analytical, heuristic, and metaheuristic algorithms [8]-[10]. Nevertheless, most of the studies in the area of DG allocation have discussed the static challenges of distribution networks.

As discussed, by increasing the penetration of the RESs in the distribution grids, the impact of such sources on the stability of the grids is no longer restricted. Among the different types of power system stabilities, transient stability is known as one of the impactful short-term stabilities that can extensively threaten power grids' security [11]. While the transient stability problem has been conventionally discussed in the transmission grids, due to the high proliferation of DGs in distribution grids, the transient stability analysis in active distribution networks has become vital [12]. In particular, transient stability analysis in the distribution grids has been addressed in several papers indicate considering various DGs including synchronous DGs [13]-[15], asynchronous DGs [16]-[19], and converter-interfaced [20]-[24].

Besides transient stability, frequency stability analysis of the power grids and the influence of the inverted-connected DGs have been addressed in [25]-[27]. These studies have indicated that the power electronic interfaces PVs and PEVs play important roles in the frequency control strategies of these sources [23], [27], and these sources should not be taken into account as negative loadings [28]. Also, some research studies have been published to reduce the impact of the mechanical deterioration of inverter-based DGs on the attenuation of frequency stability [29], [30].

Despite several papers that have addressed the transient stability impacts of the DGs, the optimal allocation of DGs considering transient stability has been investigated in [31], [32]. In [31], the authors used an objective function based on the maximization of critical clearing time to find the optimal location of microturbine DGs considering transient stability. In [32], authors have provided an approximation for kinetic energy and furthermore have introduced an OF for optimal allocation of large-scale rotational and inverter type DGs in transmission networks considering transient stability. However, approximations in modeling different types of DGs profoundly impact the accuracy of critical kinetic energy.

This paper tries to enhance the transient stability in the distribution network. More specifically, this paper targets the allocation of different types of distributed generations (DGs) considering the maximization of transient stability margin. By maximizing the transient stability margin the deterioration impacts of the inverter-based DGs on the grid stability have been dealt with. The transient stability based OF basically relies on the critical and clearing angles. The objective function (OF) is designed based on the three indices including phase angle distance from the center of inertia, maximum between DGs, and total variation of phase angles from the center of inertia. Besides transient stability, the improvement of voltage profile and minimization of power losses are taken into account. The proposed algorithm is implemented on the IEEE 33-bus test system and furthermore, several scenarios are conducted to ensure the effectiveness of the proposed algorithm under fault conditions.

The paper's structure is as follows: the proposed optimization of the transient stability enhancement is presented in *section II*. The OFs and the implementation are presented in *section III*. The simulation results and discussion of the proposed framework are presented in *section IV*. Finally, *section V* provides some comments about the achievements of the proposed algorithm.

II. Objective Functions

The optimal allocation of the multiple DGs is conducted based on the minimization of the three OFs including, transient stability, voltage profile improvement, and power losses. The formulations of the OFs and also the constraints of the grids are described in the following.

A. Transient Stability OF

The transient stability OF consists of three indices including phase angle distance from the center of inertia (COI), the maximum distance between the phase angles of DGs, and the total variation of phase angles from the center of inertia. The indices are defined as follows:

- Phase Angle Distance from COI (F_1):

$$F_1 = \sum_{i=1}^{N_g} |\delta_i(t_c) - \delta_{COI}(t_c)| \tag{1}$$

where N_g is the number of DGs, δ_i and δ_{COI} are phase angles of i-th DG and COI, respectively, and t_c is the clearing time.

- Maximum Distance Between DG Phase Angles (F2):

$$F_2 = \max\left\{\left|\delta_i(t_c) - \delta_j(t_c)\right| \middle| i,j \in N_g \ \& \ i \neq j\right\} \tag{2}$$

- Total Variation of Phase Angles from COI (F3):

$$F_3 = \sum_{k=0}^{K} \sum_{i=1}^{N_g} \left(\delta_i(\mathrm{k}) - \delta_{COI}(k)\right)^2 \tag{3}$$

where k is the counter and the summation is started from clearing time and is continued until the end of simulation (K).

The transient stability OF is defined as follows:

TABLE I. The Constrains of the Optimization Problem

Allowable Range of Bus Voltage	$\mathbf{0.94 \leq V_B^{p.u} \leq 1}$
Allowable DG Power Variation Range	$\boldsymbol{P_{DG,min} \leq P_{DG,i} \leq P_{DG,max}}$
Allowable Line Flow Capacity	$S_L \leq \lvert S_{L,\max}\rvert$

$$\mathrm{F} = \sum_{i=1}^{3} F_i \tag{4}$$

$$\mathrm{OF}_1 = Min\{F\} \tag{5}$$

B. Power losses and voltage profile improvement OFs

While the primary target of this paper is transient stability improvement, however, the improvement of voltage profile and reducing power losses are known as the most OFs in the distribution grids that directly impact the operation cost of the networks. These OFs are defined as follows:

$$\mathrm{G} = \sum_{i=1}^{N_L} \mathrm{P}_L \tag{6}$$

$$\mathrm{OF}_2 = Min\{G\} \tag{7}$$

$$\mathrm{H} = \sum_{i=1}^{N_B} (\mathrm{V}_i - 1)^2 \tag{8}$$

$$\mathrm{OF}_3 = Min\{H\} \tag{9}$$

where P_L is the loss of lines and V_i is the bus voltage.

C. Constrains

To solve the OFs, there are some constraints that should not be violated during optimization procedures which are tabulated in Table I:

III. Structure of Proposed Optimization Framework Considering Transient Stability

By installing a new DG in the distribution grids, the transient stability margin of the grids may profoundly change due to the following reasons:

- Variations of short circuit capacity depending on the DG location.
- Variations of pre-disturbance state-variables such as voltages of buses considering different DG locations.
- Variations of contributions of DGs on the acceleration power after disturbance.

Except for the DG-related factors, there are some networks factors that affect the transient stability of the distribution grids including:

- The fault occurrence probabilities of the buses are different.
- The load of the buses may vary.

As a result, it is mandatory to take into account the above factors in the optimization to find the optimal place and size of the DGs. To such aim, the following steps are carried out to find the optimal size and place of DGs:

- **Step 1:** In the first step, the data of the network and optimization algorithm is acquired.
- **Step 2:** Based on the pre-defined information given in Step 1, the initial population regarding the size and place of DGs are generated.

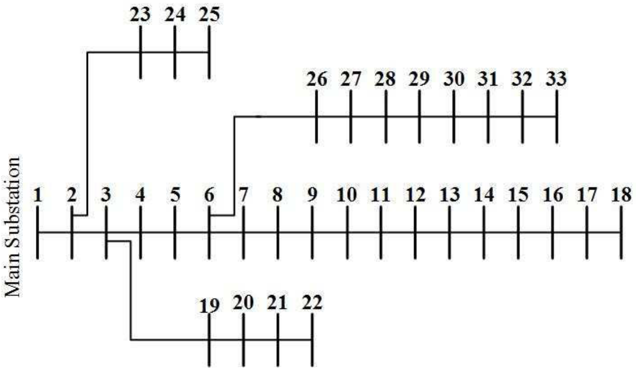

Fig. 1. IEEE 33-bus test system.

The following steps are performed in the optimization algorithm:

- **Step 3:** The load flow of the network is calculated based on the system topology.
- **Step 4:** For a certain fault location, the transient stability problem is assessed and furthermore, the objective function is calculated using (4). Afterward, the constraints associated with the load flow are checked and if the constraints are not satisfied, the OF is penalized by a large number.
- **Step 5:** Eventually, if the criterion of convergence is satisfied, the optimization procedure is finished and the output of the optimization algorithm is selected as the solution to the problem. In this paper, the criterion of convergence is a pre-defined number of iterations.

IV. PERFORMANCE ASSESSMENT AND DISCUSSION

To evaluate the effectiveness of the proposed OF in transient stability improvement of the distribution grids, IEEE 33-bus distribution network is selected as the test system. IEEE 33-bus test system which is shown in Fig. 1, operates at voltage level 12.66 kV and several commercial and residential loads with total active loads of about 3.7 MW and total reactive loads of about 2.3 MVar [33]. The effectiveness of the proposed OF is verified with/without the considerations of power loss and voltage OFs given in (7) and (9) respectively.

TABLE II. RESTRICTIONS OF THE NUMBER AND SIZE OF DGS FOR THE OPTIMIZATION PROBLEM

	Min. Size (kW)	Max. Size (kW)	Min. Number of DGs	Max. Number of DGs
SG	1000	2000	1	2
PV	500	1000	1	5
WT	500	2000	1	2

TABLE III. SPECIFICATIONS OF THE PSO ALGORITHM

Population	50
Iteration	200
Stopping Time Limit (Second)	∞

To solve the optimization problem, Table II provides the restrictions on the number and size of DGs.

To calculate the transient stability OF, only three-phase faults are randomly applied with 200 to 250 ms duration. The simulation time is considered 10 s for each case of transient stability. The proposed optimization algorithm is solved by the well-known Particle Swarm Optimization (PSO) algorithm [34]. The number of population, iteration, and stopping time limit for the PSO algorithm is provided in Table III.

A. Optimal DG Location considering transient stability OF

Here, the performance of the proposed optimization algorithm considering only the transient stability OF is presented. Knowing the number of DGs, the best size and location of the DGs are obtained on the IEEE 33-bus test system and the results are shown in Table IV.

The optimal locations and sizes provided in Table IV demonstrate considering a different number of DGs, OF will converge to a minimum value. Besides, as it can be seen in the results given in Table IV, case 2 with a total of 4 DG has the minimum OF among the cases.

To show the effectiveness of the proposed framework, an index is required to determine the overall transient stability issue of the grid considering different fault locations, types, and durations. In [35], a probabilistic index for transient stability assessment is developed considering different types of DGs. Here, this probabilistic index is employed to evaluate the transient stability margin of the distribution grid for different arrangements of DGs. Also, to better demonstrate the effectiveness of the proposed algorithm, for each case, the probabilistic index of transient stability for a set of random DGs is calculated. As it can be seen in Fig. 2, for all optimal solutions, the PDFs of CCT are shown greater values compared with the ransom sets of DGs. Furthermore, the transient stability margin of the most optimum case, i.e., case 2, is significantly enhanced compared with other solutions. As it can be revealed from Fig. 2, as the number of PV-based DGs are increased, the transient stability will be deteriorated due to reducing the mechanical inertia. However, employing the proposed algorithm helps to increase the transient stability preservation. Also regardless of DG type, the random locations of DGs have resulted in less transient stability margin which indicates the necessity of the attention to the transient stability in the optimal DG allocation.

TABLE IV. OPTIMAL SOLUTION OF THE PRESENTED FRAMEWORK

Case	Total Number of DGs	SG		WT		PV	
		Location	Size	Location	Size	Location	Size
1	3	23	2000	27	1000	9	1000
2	4	30	2000	25	500	20, 8	1000, 1000
3	5	12	1000	20	1000	22, 23, 31	1000, 1000, 500
4	6	20	1000	24, 25	1000, 500	11, 28, 33	1000, 1000, 500

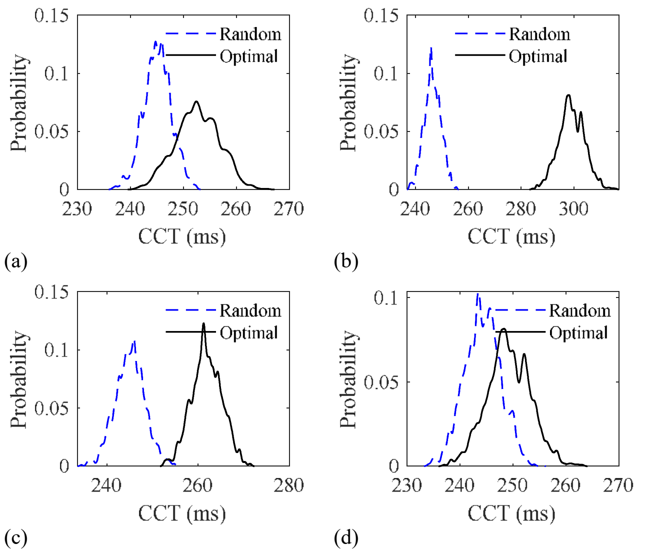

Fig. 2. PDFs of CCT after optimal and non-optimal locating sets of DGs considering transient stability OF.

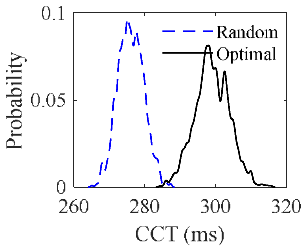

Fig. 3. PDFs of CCT after optimal and non-optimal locating sets of DGs considering all OFs.

B. *Optimal Location of DGs considering all OFs*

Here, the performance of the proposed optimization algorithm considering static and dynamic OFs is discussed. The optimal solutions are obtained considering equal weighting factors for all OFs. Unlike the previous case study, the most optimum solution considering all OFs is obtained for a set of 5 DGs including one SG with 1000 kW capacity installed at bus 20, one WT with 500 kW capacity installed at bus 33, and three PVs with capacities 1000 kW, 1000 kW, and 500 kW installed at buses 23, 24, and 18 respectively. As it can be seen in Fig. 3, transient stability has significantly improved even though the number of PV has increased.

For the optimal solution, the voltage profile with/without considering TS OF is shown in Fig. 4. As it can be seen in Fig. 4, the voltage profile without considering TS OF is significantly improved Nevertheless, considering the benefits of TS OF, it can be seen the improvement of voltage with considering TS OF is notable.

V. Conclusion

Installing different types of DGs in distribution grids have economical and operational advantages for the power grids. However, different technologies of DGs may put the stability of the grids in great danger. Especially for inverter-based DGs that deteriorate the system's mechanical inertia. A new OF was put forward for allocating the different types of DGs in the distribution network concentrating on the enhancement of transient stability. The proposed OF was based on the DG's rotor angle at the time of fault clearance, and COI's phase angle. The primary target was to find the optimal solution for the size and location of DGs in the distribution grids. Besides the transient stability, voltage profile improvement and power loss reduction are also considered in the proposed optimization framework. It was concluded that the proposed

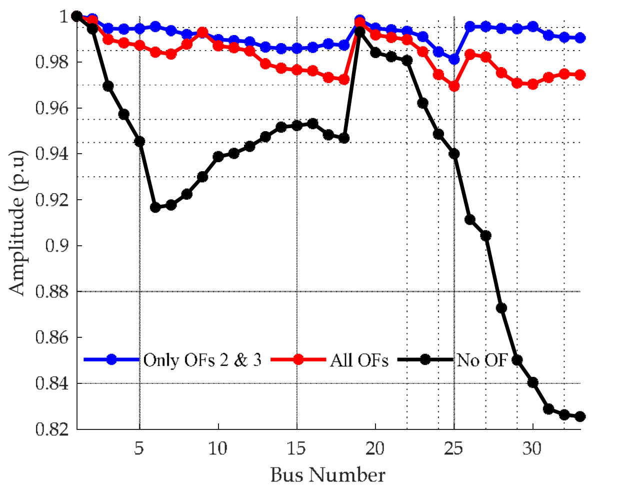

Fig. 4. Voltage profiles of test system before and after DG allocation.

algorithm optimally allocates SG, WT, and PV and finds the maximum margin of transient stability considering different sizes and locations. It was also investigated that the lack of consideration of transient stability during the allocation of DGs will put the distribution grid in a vulnerable position. Also, using the proposed algorithm, the vulnerability level of the grids in presence of high penetration of inverter-based DGs was evaluated. According to the simulation results, it can be inferred the proposed algorithm can properly find the location and size of different types of DGs considering the enhancement of transient stability withstanding.

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