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A Multi-Objective Problems for Optimal Integration of the DG to the Grid using the NSGA-II

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***Abstract*— In recent years, integration of a wide variety of Distributed Generation (DG) technology in distribution networks has become one of the major management concerns for professional engineers. In this paper, one type of the DG i.e. Wind Turbine is optimally integrated in a power network for enhancing the performance of the network. A new variant of Genetic Algorithm (GA) dedicated in multi¬objective optimization problems known as Non¬dominated Sorting Genetic Algorithm II (NSGA-II) has been proposed for accomplishing the same. To aid the decision maker choosing the best compromise solutions from the Pareto front, the fuzzy¬based mechanism is employed for this task. The NSGA¬II is used to obtain the optimal integration and sizing of the DG in a suitable load bus of the system. Multi-objective functions are considered as the indices of the system performance viz: maximization of system loadability in system security and stability margin i.e. voltage and line limit whereas minimization of the real power loss of the transmission lines. Simulation studies are undertaken on modified IEEE 14¬bus and a practical Indonesia Java¬Bali 24¬bus systems. Results show that the dynamic performance of the power system can be effectively improved by the optimal integration and sizing of the DG.**

Keywords*— *DG; Multi¬objective optimization; NSGA-II; security and stability margin; system loadability.

I. INTRODUCTION

The growing awareness of environmental issues and efforts to reduce dependency on fossil fuel resources are bringing renewable energy resources to the mainstream power sector. Among the various renewable resources, Distributed Generation-based wind power is assumed to have the most profitable technical and economic prospects [1]

The applications of DG in power system have received wide attention and scope in power system for several reasons. First, the DG helps to utilize the distributed but with small energy resources. Second, reducing the use of transmission capacity as most DG is located near the center of the load along with several types of DGs also provide reactive power to support the power system. Third, as the DG is located close to the load thus, it reduces transmission losses and at the same time improving system performance. The fourth advantage is to delay the investment in transmission lines and construction of large power plants. Above all, second option/advantage has been utilized in this chapter to enhance the system loadability by optimal placement of DGs in the network [2].

On the other hand, integration of a wide variety of DG technology in distribution networks has developed one of the major management concerns for professional engineers. Some of the major technical benefits are improved voltage profile by reducing active power losses, enhanced system security and reliability for power quality improvement, increased overall energy efficiency [3] relieved transmission, and distribution congestion.

A lot of work was made on the optimal allocation of DG for different purposes. Different approach techniques have been suggested i.e., Genetic Algorithm (GA) [1], Quantum GA for optimal location and settings of multi-types of DG [2]. However, the system stability and security constraints are not entirely considered yet for maximizing the system loadability within any condition of the grid and their impact on the transmission loss with optimal integration of DG.

From these literature works, it can be observed that most of the problems for optimal location of DG was mostly expressed disparately as a mono¬objective optimization problem [1],[2]. Unfortunately, the formulation of the problems as a mono-objective optimization is not quite practical. However, it is always good to take advantage of DG considering and minimize the interaction by formulating as a multi¬objective problems and solve them simultaneously.

In this work, multi-objective problems have been formulated for maximizing the system loadability by optimal location and sizing of a DG, viz. Wind generation system or farm while maintaining the system security and stability margin within acceptable range. By means of DG optimal integration, the active power loss of the transmission systems was also minimized. The multi-objective problems have been solved simultaneously using the new variant of GA specialized in multi-objective optimizations problem, namely the NSGA¬II.

II. MODELING OF DG

So far, there are several technologies from the DG of renewable technologies viz: solar, photovoltaic, wind, geothermal, ocean, etc. The DG units are modeled as synchronous generators for small hydro power, geothermal power, combined cycles and combustion turbines. They are treated as induction generators for wind and micro hydro power. DG units are considered as power electronic inverter generators such as micro gas turbines, solar power, photovoltaic power and fuel cells [4].

In this paper, the type 3 of the DG namely doubly fed induction generators (DFIG) has been employed which are applied for the energy conversion, called as variable speed

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systems, the power electronic interface which is used to connect DGs with utility, also provides some reactive power support. References [5] provide a detailed description of the operation of a DFIG.

III. PROBLEM FORMULATION

As indicated, the goal of the stated optimization problem is the optimal integration of DG into power network in order to maximize the loadability, with security adns stability margins, and minimize the real power loss in transmission lines. The optimal integration and sizing of DG is formulated as a real constrained mixed discrete continuous multi-objective optimization problem that has two objective functions to be optimized simultaneously:

$$\text{Minimize } F(\mathbf{x},\mathbf{u}) = [F_1(\mathbf{x},\mathbf{u}),\ F_2(\mathbf{x},\mathbf{u})] \tag{1}$$

$$\text{Subject to } : \begin{cases} g(\mathbf{x},\mathbf{u}) = 0 & j = 1, \ldots, M \\ h(\mathbf{x},\mathbf{u}) \le 0 & k = 1, \ldots, K \end{cases} \tag{2}$$

where F is known as the objective vector, F1 and F2 are the bi-objective functions to be optimized, x is the vector of dependent variables, and u is the vector of control variables.

In all optimization problems several cases in terms of use of the DG are considered namely: (a) Case-1: base case, (b) Case-2: with DG. The objective functions considered in this paper are presented in detail as given below.

A. *Maximize the system loadability within security margin*

$$\text{Maximize } F_1(\mathbf{x},\mathbf{u}) = \{\lambda_1\} \tag{3}$$

$$\text{Subject to } \quad VL = \sum_{i=1}^{N_L} OLL_i + \sum_{j=1}^{N_E} BVV_j \tag{4}$$

where VL is the thermal and bus violation limit factor, OLL_i and BVV_j represent the overloaded line factor and branch the bus voltage violation factor respectively and will be expatiated on later; N_L and N_E are the total numbers of transmission lines and load buses respectively; and λ_l is a load parameter of the system, which aims to find the maximum amount of power that the network is able to supply within system security margin. The load parameter λ_l in (3) is defined as a function of a load factor λ_f [6]:

$$\lambda_1 = \exp[\,\gamma \left| \lambda_f - \lambda_f^{\max} \right|] \qquad \lambda_f \in [1, \lambda_f^{\max}] \tag{5}$$

where is the coefficient to adjust the slope of the function, and $\lambda_f{}^{\max}$ is the maximal limit of λ_f . The load factor λ_f reflects the variation of power demands P_{Di} and Q_{Di} , which are defined as:

$$P_{Di}(\lambda_f) = \lambda_f P_{Di} \tag{6}$$

$$Q_{Di}(\lambda_f) = \lambda_f Q_{Di} \tag{7}$$

where i = 1, …. ,N_D and N_D is the total number of power demand buses. λ_f = 1 indicates the base load case.

The index of system security state contains two parts [4]. The first part, OLL_i, relates to the branch loading and penalizes overloads in the lines. The value of OLL_i equals to λ_l if the jth branch loading is less than its rating. OLL_i increases logarithmly (actual logarithm) with the overload. The second part BVV_j in (4) concerns the voltage levels for each bus of the power network. Similar to OLL_i, The value of BVV_j equals to λ_l if the voltage level falls between the voltage minimal and maximal limits. Outside the range, BVV_j increases exponentially with the voltage deviation.

B. *Minimization of Real Power Loss of the transmission lines*

This objective is to minimize the real power loss (P_{loss}) in the transmission lines and which can be expressed as [7]:

Minimize $P_{loss,}$

$$F_2(\mathbf{x},\mathbf{u}) = P_{loss} = \sum_{k=1}^{nl} g_k \left[V_i^2 + V_i^2 - 2V_iV_j \cos\iota(\delta_i - \delta_j) \right] \tag{8}$$

Where, nl is the number of transmission lines; g_k is the conductance of the k^{th} line; $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltages at the end buses i and j of the k^{th} line, respectively.

C. *Equality Constrints*

These constraints represent the typical load flow equations as follows:

$$P_{G_i} = P_{D_i} + V_i \sum_{i=1}^{N_i} V_j \left(G_{ij} \cos\theta_{ij} - B_{ij} \sin\theta_{ij} \right);\ i = 1, \ldots N_0 \tag{9}$$

$$Q_{G_i} = Q_{D_i} + V_i \sum^{N_i} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right); i = 1, \ldots N_{PQ} \tag{10}$$

Where N_i is the number of buses adjacent to bus i including bus i, N_{PQ} and N_0 are the number of PQ buses and total buses excluding slack bus, respectively.

D. *Inequality Constraints*

The inequality constraints h(x, u) are limits of control variables and state variables. Generator active power PG, reactive power QG and voltage VG are restricted by their limits as follows:

$$\begin{aligned} &P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max} && i = 1, \ldots\ldots, N_G \\ &Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max} && i = 1, \ldots\ldots, N_G \\ &V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max} && i = 1, \ldots\ldots, N_G \end{aligned} \tag{11}$$

The constraints of load voltages at load buses V_L and transmission loading P_L are represented as:

$$\begin{aligned} &V_{L_i}^{\min} \le V_{L_i} \le V_{L_i}^{\max} && i = 1, \ldots\ldots, N_L \\ &\left| P_{L_i} \right| \le P_{L_i}^{\max} && i = 1, \ldots\ldots, N_E \end{aligned} \tag{12}$$

E. *Power System Stability dan Security Margins*

- *Fast Voltage Stability Index*

Fast Voltage Stability Index (FVSI) proposed by Musirin [8] is utilized in this paper to assure the safe bus loading. The line that exhibits FVSI close to 1.00 implies that it is approaching its instability point. If FVSI goes beyond 1.00, one of the buses connected to the line will experience a sudden voltage drop leading to the collapse of the system. FVSI index incorporation in the controller assures that no bus will collapse due to overloading.

- *Line Stability Factor*

System stability index is also assured by Line Stability Factor (LQP) proposed by A Mohamed et al [9]. The LQP should be less than 1.00 to maintain a stable system. LQP assure the controller that no line is over loaded under any grid condition.

IV. NON DOMINATED SORTING GENETIC ALGORITHM (NSGA-II)

A. NSGA-II Optimization Principle

The capabilities of multi-objective genetic algorithms (MOGAs) to explore and discover Pareto optimal fronts on multi-objective optimization problems have been well recognized. It has been shown that MOGAs outperform traditional deterministic methods to this type of problem due to their capacity to explore and combine various solutions to find the Pareto front in a single run. We will implement a multi-objective optimization technique called the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), which is described in detail by Deb et al. [10]

B. Best Compromize Solution

Once the Pareto optimal set is obtained, it is practical to choose one solution from all solutions that satisfy different goals to some extends. Due to the imprecise nature of the decision maker's (DM) judgment, it is natural to assume that the DM may have fuzzy or imprecise nature goals of each objective function [7]. Hence, the membership functions are introduced to represents the goals of each objective function; each membership function is defined by the experiences and intuitive knowledge of the decision maker. In this study, a simple linear membership function was considered for each of the objective functions.

V. SIMULATION

The NSGA II algorithm is carried out in the modified IEEE 14-bus test system [5]. The type DG incorporated in this simulation is Variable Speed Wind Turbine with DFIG which injects both active and reactive power. The loads are typically represented as constant PQ loads with constant power factor, and increased according to (6) and (7). The DG should be formed at low voltage side, consisting of buses.

TABLE I. NSGA-II PARAMETERS

Population	**Generation**	**Pool Size**	**Tour Size**	η_c	η_m
100	100	25	2	20	20

The number of DG is specified by user, here as equal one and only DG type 3 is considered. The parameters of NSGA-II for all optimization cases are summarized in Table I.

A. IEEE 14-bus system

This test system [5], consists of two generators, located at buses-1 and 2; three synchronous compensators used only for reactive power support at buses-3, 6, and 8. The best locations, sizings of the DG, maximum system loadability (SL) and minimum active power loss (Ploss) have been obtained using the NSGA-II technique for each case as given in Tables II, and III. The Pareto fronts for the best compromise solutions of all cases for the bi-objective optimizations are also presented in Figs. 1 and 2, respectively.

- *Case-1: basecase (without DG)*

For base case, the SL and P_{loss} have been obtained as given in Table II using the NSGA-II technique which the Pareto fronts for the best compromise solution (CS) of the case for the bi-objective problem is presented in Fig. 1.

TABLE II. OPTIMAL SL FOR BI-OBJECTIVES OPTIMIZATION OF IEEE14-BUS SYSTEM

	Location	*Sizing*		*SL(F₁)*	*Ploss(F₂)*
	(bus)	*MW*	*MVAR*	*(%)*	*(pu)*
Best SL	-	-	-	*149.59*	*0.3593*
Best P_{loss}	-	-	-	*111.51*	*0.1625*
Best CS	-	-	-	*114.40*	*0.1704*

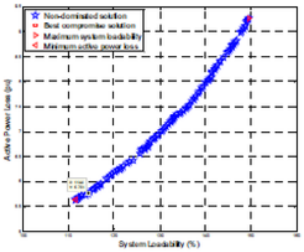

Fig. 1. Pareto front of base case for bi-objective optimization of IEEE 14-bus system.

- *Case-2: with DG*

The obtained results for Case-2 presented in Table III indicate that the best CS of optimal integration of the DG within the network by considering all stability constraints is found at bus 8 with size of 49.91 MW and -11.56 MVAR.

TABLE III. OPTIMAL INTEGRATION OF DG FOR BI-OBJECTIVES OPTIMIZATION OF IEEE14-BUS SYSTEM

	Location	*Sizing*		*SL(F₁)*	*Ploss(F₂)*
	(bus)	*MW*	*MVAR*	*(%)*	*(pu)*
Best *SL*	8	87.52	-3.24	157.08	0.4885
Best P_{loss}	14	47.47	-17.34	112.24	0.1772
Best *CS*	8	49.91	-11.46	128.27	0.2239

Whereas in Fig. 2 shows the Pareto front of the optimization problem of this case, in the objective space of *SL* and P_{loss}. This set of solutions on the non-dominated frontier is used by the decision maker as the input to select a final CS by using the normalized membership function.

Moreover, the installation of the DG at the same bus provides the best *SL* of 157.08 % as well but with the P_{loss} of 0.4885 pu which is the highest in this case. In addition, this *SL* is quite large compare with the result obtained in base case as given in Table II. The best P_{loss} in this case have been obtained of 0.1772 pu by installing the DG at bus 14 but it can increase the SL only 112.24% which is the lowest SL the this case.

The voltage and line stability indices represented by FVSI and LPQ for case-2 is quite less than 1.00 as depicted in Fig. 3. These indices are used to maintain grid stability at various levels of *SL* which ensure that no bus will collapse due to overloading and no line is over loaded under any grid condition.

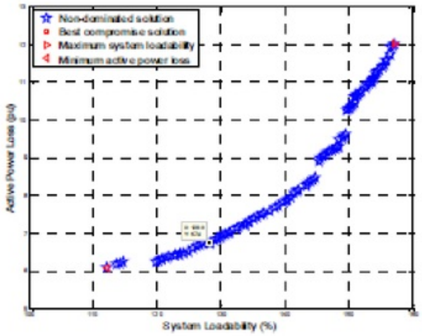

Fig. 2. Pareto front to find optimal integrations and sizing of DG for biobjective optimization of IEEE 14-bus system.

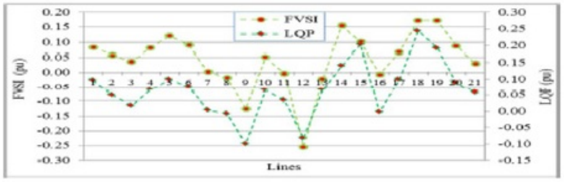

Fig. 3. FVSI and LQP of optimal integrations and sizing of DG for IEEE 14-bus system.

When compare with [1], the proposed results need more 31.37 MW size of DG to increase SL of 12.24 % but P_{loss} is higher 12.84 % than the result in [1] as shown in Table IV. With the same location at bus 14, the result obtained in [3] is required less of 7.77 MW size of DG compare with the proposed method to find P_{loss} of 28.83 MW. The P_{loss} is higher 62.7 % compared with the proposed method. Moreover, the SL by considering all stability constraints of the standard IEEE 14-bus test system are not incorporated in [1] and [3]. Therefore, the suggested approach in this paper has been found as more suitable and practical compared with reported literature for similar work.

TABLE IV. OPTIMAL INETRATION, SL, SIZE, P_{LOSS} AND MINIMUM NUMBER OF DG (N) NEEDED IN IEEE 14-BUS SYSTEM

Obtained Results of DG integration	***N***	***SL (%)***	***Total Size (MW)***	***P_{loss} (MW)***	***Optimal Locations (bus)***	***Considered stability (section F)***
Proposed method	1	112.24	47.47	17.72	14	Yes
[1]	1	100	16	11.70	8	No
[3]	2	100	40	28.83	14	No

B. Indonesia Java-Bali 24-bus system

In order to give a more real feature to this study, the proposed method has been applied on the practical Indonesia Java-Bali 24-bus grid system which has 8 generators and 49 lines [11] as shown in Fig. 4. The total active and reactive load of the system are 10570.87 MW and 4549.23 MVAR respectively. Table V summarizes that the extreme points and the optimal integration of the DG for bi-objective optimization of this system using the suggested technique.

The results obtained in Table V indicates that the best CS with optimal integration of DG to the grid is found at bus-13 (CLGON) as the best locations of the DG, with sizing of 57.04 MW and -19.54 MVAR. The Pareto fronts for the best CS of is obtained as shown in Fig. 5. The stability of the system represented by their FVSI and LQP are also less than 1.00.

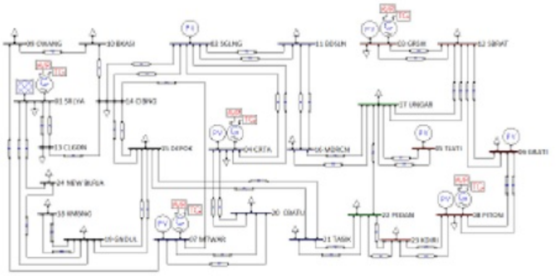

Fig. 4. Single line diagram of Indonesia Java-Bali 24-bus system

TABLE V. OPTIMAL INTEGRATION OF DG FOR BI-OBJECTIVES OPTIMIZATION OF INDONESIA JAVA-BALI 24-BUS SYSTEM

	Location	***Sizing***		***SL(F_1)***	***P_{loss}(F_2)***
	(bus)	***MW***	***MVAR***	***(%)***	***(pu)***
Best SL	*14*	*142.54*	*-51.17*	*159.45*	*4.0471*
Best Pl_{oss}	*13*	*57.04*	*-19.54*	*129.00*	*1.1917*
Best CS	*13*	*57.04*	*-19.54*	*129.00*	*1.1917*

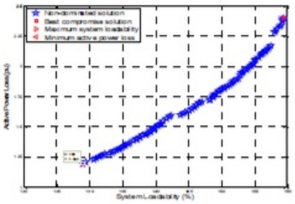

Fig. 5. Pareto front to find optimal integration of DG for bi-objective optimization of Indonesia Java Bali 24-bus system.

VI. CONCLUTIONS

A novel approach based on NSGA-II has been presented in this work and applied to optimal integration, and sizing of one type of DG in power network. The problem is formulated as a real mixed continuous integer multi-objective optimization problem. Two different problems are considered viz, maximize system loadability (*SL*) and minimize real power losses (P_{loss}) have been simultaneously solved as a bi-objective optimization problem. In each case, the optimal integration, and sizing of the DG are performed for several uses of the devices by considering security and stability constraints. To maintain the Pareto front size, a crowding distance technique is used; moreover, a fuzzy based mechanism is engaged to extract the best compromise solution from the Pareto front. The results show that the NSGA-II provides well distributed non dominated solutions and well exploration of the research space.

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