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Optimal Penetration of RES to the Network by PSO-based Microgrid-Controller

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Abstract - **Penetration of renewable energy resources (RES) to the grid lacking a significant system redesign is one of the main issues that need to be studied. An effective technique for solving this problem is optimizing the penetration of these units into a microgrid, the gateway to emerging a smart grid. The paper investigates the consequence of microgrid integration into the grid to achieve safe maximum instantaneous RES penetration. The microgrid models include solar PV, energy storage, and wind energy (WE). The) wind energy type double-fed induction generator (DFIG) is integrated into the grid's dynamic model system by considering the automatic voltage regulator and the turbine governor. The maximum acceptable load on each bus is determined explicitly by the Algorithm. The artificial intelligence-based particle swarm optimization (PSO) method has been utilized in the controller to attain the optimal harmless rapid WE penetration limit. The results seem encouraging when examined on a modified IEEE 14-bus with a microgrid system.**

Index Terms - **Microgrid, Penetration, Particle Swarm Optimization, Renewable Energy, Wind Turbine.**

INTRODUCTION

To encourage decarburization, the need for renewable energy resource power plants (RES) in the electricity sector to meet community demands is inevitable. Wind energy and solar generation, among various RES, are projected to attain the most actual interconnection [1]. As the use of RES increases, the network has many instability problems. Undesirable system circumstances, in particular, loss of synchronization, voltage failure, load shedding, and significant voltage and frequency deviations, can accrue due to large-scale RES integration into the grid. The integration can also cause flicker and harmonics that cause high transmission and distribution line losses, overload, and increased power oscillations [2],[3]. Integrating RES land, represented as Distributed Generation (DG), into the most suitable bus into the grid is one solution for the evacuation and proper grid control strategy to obtain optimal RES penetration. The DFIG is a widely used type of wind turbine because it has many advantages [4] compared to other classes used in this work.

Another type of DG is solar photovoltaic (PV)-based solar energy, which is versatile, easy to maintain, simple to install, and can be carried out close to the user's load point. Small critical installation loads primarily use a storage system, such as start-up and control. RES penetration into the grid is the ratio of RES energy to the grid in a given period to the total amount of power supplied to the grid from all sources [5]. Calculating the earlier factors has become a trade confidential of the electricity authority, and many rejections of RES are ongoing [6]. With the integration of photovoltaic (PV) systems into the grid via power electronics converters, as in [7], the DG landscape is changing drastically. In addition to the integrated DG, it can increase the voltage profile of the distribution network; net power will flow upstream when the DG generates more power than the local demand [8]. This study suggests an algorithm that can optimize the integration of DG in the grid by maintaining all operational controls and constraints within the allowable restrict.

The main problem with DG is integrating into the grid without requiring a significant system redesign. The demand for improved system reliability involves utilities connecting these generating sources to nearly the load [9]. An efficient method to solve this is integrating these units into the microgrid [10], the first step in developing a smart grid. Most studies in maximum wind energy penetration considering seasonal variations were conducted using stochastic analysis [11], supposing a constant wind absorption refusal factor. It has become a trade secret of the electricity authority by calculating the above factors despite the ongoing rejection of RES [6].

As a result of a paradigm shift from centralized to distributed power generation, the role of DG in the distribution network gets a more significant proportion. In PV systems, as in [7], the integration of power electronics converters is required to integrate DG into the grid. DG's landscape is changing drastically; wind energy and micro hydro turbines contribute to it. However, because DG sources are highly dependent on climate and geographic location, not all are stable or sustainable sources [12].

The literature [13]-[15] shows that DG can inject clean power that will flow upstream to the substation to affect distribution network performance such as; voltage profile, line power loss, system security, and stability.

This work proposes a methodology for developing an appropriate control algorithm to optimize the penetration of RES into the grid integrated into the microgrid by involving artificial intelligence (AI) based on heuristic techniques. The proposed Algorithm is required to develop a comprehensive problem formulation concerning dynamic microgrid modeling, including solar PV, fuel cells, wind farms, and grid systems. To solve the grid performance in high-RES penetration, various safety and system stability indices such as voltage stability index and line stability factor, as well as eigenvalue analysis, are considered in developing the formulation algorithm of the complete grid system. An AI-based microgrid control algorithm using the PSO technique was tested using the IEEE 14-bus standard test system to achieve maximum penetration of RES into the grid. This technique investigated the improvement of system performance to control grid parameters.

METHODOLOGY

This study develops an algorithm to maximize the penetration of RES into the grid with PSO-based microgrid control techniques. The problem formulation is carried out in detail with dynamic modeling, including wind farms, solar PV, and fuel cells, as a microgrid system that is interconnected to the grid. The next step integrates the wind farm into the microgrid model, which is finalized by calculating the maximum instantaneous penetration of the wind farm using a defined AI algorithm. A microgrid having total generating capacities varying from a few hundred kilowatts to several megawatts are low or medium-voltage networks with DG sources, local storage devices, and loads, both critical and non-critical [16]. It can operate in network-connected mode and isolated or island mode. In the first mode, the microgrid operates while still being integrated into the grid. Still, if there is a disturbance in the network, the microgrid will be disconnected from the grid by a static switch to enter island mode. In this condition, the supply to the critical load is uninterrupted. Since the disturbance has been resolved, the microgrid will be integrated into the utility network through a resynchronization process. To ensure grid stability and security are achieved, it is necessary to develop a microgrid with different configurations using smart grids [7].

I. Wind Turbine Modeling

Wind energy modeling in this work is expressed as a composite distribution by including the mean, ramp, turbulence, and wind gust components to consider the composite properties [17]. Because of its advantages, the doubly fed induction generator (DFIG) type [18] is the wind turbine generator chosen, as shown in Figure 1. This type of turbine has a rotor connected via slip rings and a power electronic converter, while the stator is directly connected.

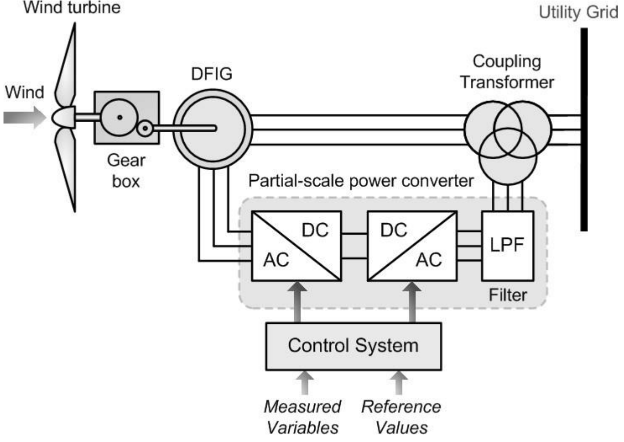

FIGURE 1 WIND TURBINE MODELING BASED ON DFIG

II. Photovoltaic Generators Modeling

Photovoltaic generators, which have high-cost but low-efficiency characteristics, have recently gained popularity among electricity utilities. This generator consists of strands of solar cells which form an electrical circuit, as formulated in (1) [8].

$$\left.\begin{aligned} i_{dc} &= i_L - i_D - V_D / R_{sh} \\ 0 &= V_D - V_{dc} - R_{se} i_{dc} \\ 0 &= i_s(\theta)(e^{V_D/\gamma_\theta(\theta)} - 1) - i_D \end{aligned}\right\} \tag{1}$$

III. Battery Energy System

Several types of batteries are voltage sources depending on the current generated and the battery's charging status. One of the dynamic rechargeable battery models, whose mathematical model is shown in (2), is based on the classical shepherd model [19].

$$\left.\begin{aligned} q_e &= i_{dc} / 360 \\ i_m &= (i_{dc} - i_m) / T_m \\ 0 &= iv_{oc} - V_p(q_e, i_m) + v_e e^{-\beta_e q_e} - R_i i_{dc} - V_{dc} \end{aligned}\right\} \tag{2}$$

PROBLEM FORMULATION

I. Objective Function

The objective function is formulated to solve the penetration problem to maximize RES on the grid system, as shown in (3). P_R, P_W, and P_S represented the total real power output of all renewable, wind, and solar farms.

$$Max.\ \ P_{\mathrm{R}} = P_{\mathrm{W}} + P_{\mathrm{S}} \tag{3}$$

II. Optimization Algorithm.

In this study, to determine the optimal load bus system and simultaneously resolve the maximum secure, instantaneous penetration of the DFIG, an artificial intelligence (AI)-based heuristic method, namely the Particle Swarm Optimization (PSO) algorithm [20]-[22] was used.

The fitness function developed as formulated in (4). Where $I_{wjp}=1$; if $6\le W_j\le 9$; $R_{wj}=2$; if $W_j\le 6$; $R_{wj}=3$; if $W_j\ge 6$; $R_{vj}=0$; for generator buses, high to low voltage ratings*; and* $R_{TVj}=1/abs(TV)$; $R_{il}=1/R_{lj}$.

$$I_{\mathrm{wpj}} = R_{\mathrm{wj}} + C_{\mathrm{v}} R_{\mathrm{vj}} + \frac{1}{C_{\mathrm{TV}}} C_{\mathrm{TVj}} + \frac{1}{C_{\mathrm{l}}} R_{\mathrm{lj}} + i_{\mathrm{grid,\,j}} \tag{4}$$

$I_{grid,j}$ =0; for other primary grid systems, $I_{grid,j}$ = number of buses in the small grid of load buses connected to one node of the leading network. The constants have been selected according to the grid by setting the appropriate weights. The voltage of the weakest bus node is determined based on the tangent vector, and the buses' voltage and tangent vectors are sorted from a higher value to a lower value. Meanwhile, the AI-based PSO technique was run through a Newton Rapson power flow study to identify wind farms' best location and optimal capacity on a microgrid-connected grid.

III. Power Balance Constraint.

Equality constraints must be met at each time interval according to the provisions of the power flow study. This constraint includes the nodal power balance equation, and active and reactive power, as shown in (5).

$$\left.\begin{aligned} P_i &= P_{G_i} - P_{D_i} - \sum_{j=1}^{N_b} |V_i||V_j||V_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \\ Q_i &= Q_{G_i} - Q_{D_i} - \sum_{j=1}^{N_b} |V_i||V_j||V_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \end{aligned}\right\} \tag{5}$$

IV. Generation and Operating System Constraints.

The generation and operating system constraints to solve the maximization of penetration problem to RES on the grid system are shown in (6).

$$\left.\begin{aligned} &P_{G_i\min} \le P_{G_i} \le P_{G_i\max} \\ &Q_{G_i\min} \le Q_{G_i} \le Q_{G_i\max} \\ &|V_{i\ \min}| \le |V_i| \le |V_{i\ \max}| \\ &|MVA_{line\ \min}| \le |MVA_{line\ \max}| \end{aligned}\right\} \tag{6}$$

V. Wind Turbine Constraint.

For distribution, the wind power used [17] should not go beyond the accessible wind power from the wind farm. The constraint is formulated in (7).

$$P_D - P_L - \sum_{1}^{M} P_{G_i} - P_W \ge 0 \tag{7}$$

VI. System stability constraints.

a. Fast Voltage Stability Index (FVSI).

In this study, the FVSI voltage instability suggested by Musirin in [23] was applied to ensure safe bus loading, as formulated in (8).

.
$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{8}$$

When the line reaches the FVSI value of 1.00, the system approaches its point of instability. Any of the buses connected to the line will experience a rapid voltage drop causing the system to collapse if the FVSI value exceeds a value of 1.00. Thus the FVSI index in the control system is used to guarantee that no bus collapses due to overload. [24].

b. Line Stability Factor (LQP)

In addition, the system's stability has been guaranteed by the LQP proposed by A Mohamed et al. [25],[26]. The line stability factor (LQP) value must be lower than 1.00 to maintain the system's stability, whose formulation is given in (9). The controller can also guarantee that no line is overloaded under network conditions.

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \tag{9}$$

c. Small Signal Stability.

In the DFIG integrated system grid, the small signal stability model is expressed as $\Delta_x = A\Delta_x$, where A and x are the system state matrices and the state vector $A=F_x-F_yG_y-1G_x$, respectively. Fx, Fy, Gy, and Gx define the jacobian power flow matri$_x$. A system is considered stable in the sense of a small signal if the power system can withstand small disturbances with the complex eigenvalues of the linear equation of state having a negative real part [27]. Expression (10) shows the stability analysis based on the eigenvalues [28], which are included as a small signal stability constraint.

$$E_j(F_x, F_y, G_y, G_x) \le 0 \tag{10}$$

Result And Discussion

In this study, a modified IEEE 14-bus standard test system [24] integrated with a microgrid was used to test the effectiveness of the proposed method. The modification of the test system is modeled using the power system analysis toolbox (PSAT), as shown in the single-line diagram in Figure 2. Using the RES placement index [29], bus-3 is declared the most suitable bus for integrating DFIG into the grid.

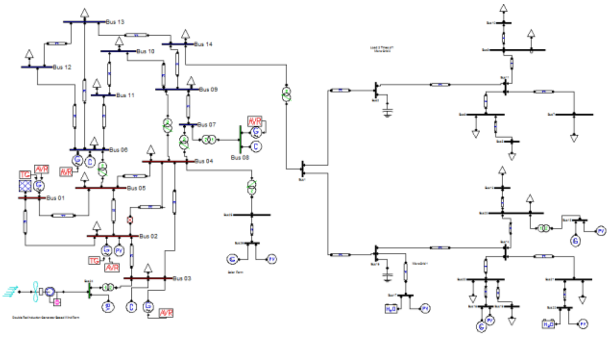

Figure 2 Modify Of IEEE 14-bus With A Microgrid Test System

I. *Maximum RES Penetration*

The bus load is increased to get maximum RES penetration, and the renewable generation shares the enhanced load. Under variable loading conditions, the slack bus only provides dynamic offsets. The results prove that the maximum load reaches 5,478 p.u. by maintaining system stability, and both active and reactive power plants satisfy the specified constraints. The additional load came to 1,8168 p.u. from the base-case load is close to 3.6612 p.u. It is only possible by the action of the controller with renewable penetration. The bus voltage profile is kept within permissible limits, i.e., 0.9 to 1.1 p.u. The maximum possible renewable penetration for a microgrid test system is up to 40.07% by integrating Solar farms into the bus: 20, 23, and 32. Figure 2 shows that the solar field is connected to buses 20, 23, and 32, whereas the wind field is installed to bus 30, which shares most of the load in the system.

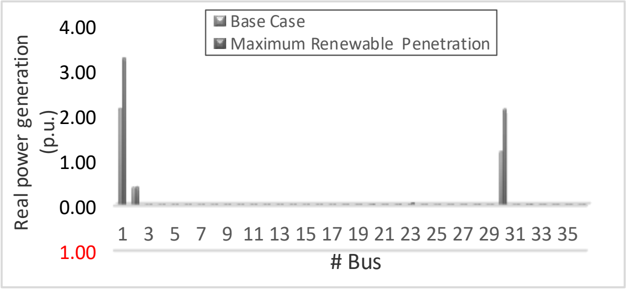

Figure 3 Real Power Generation In Numerous Wind Penetration Techniques

The maximum penetration of RES reached 2.1950 p.u., as shown in Figure 4. It is clear from the Figure that through the control measures, an increase in RES penetration achieved 0.96 p.u.

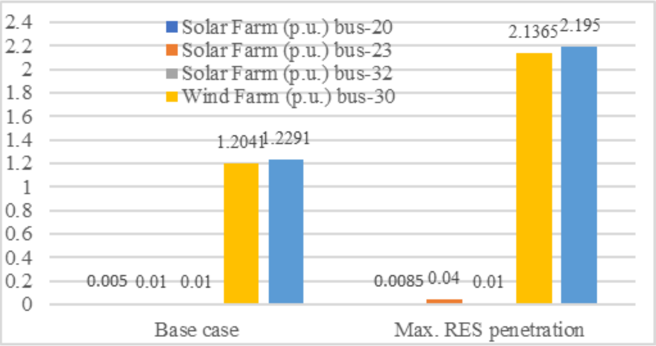

Figure 4 Graphic Of The Maximum Res Penetration

II. *Bus Voltage Profile*

Figure 5. shows the bus voltage profile within the permissible limits, from 0.9 to 1.1 p.u. at maximum penetration obtained by network reactive power management through controller action.

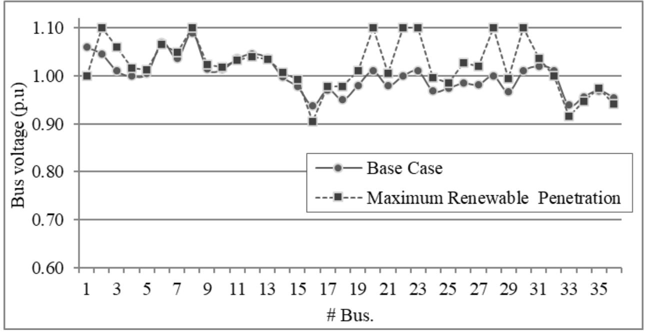

Figure 5 Wind Turbine Modeling Based On DFIG

Figure 5. Voltage profiles in the maximum wind penetration

III. *Increase Real Power Load.*

The increase in real power load at maximum wind penetration is shown in Figure 6. The Figure shows that the highest load increase occurs on bus 3, which is more than 2.5 p.u. On bus 4, the load increase only reaches one p.u. While on other buses there is almost no increase in load. Increased load on some buses due to controller action.

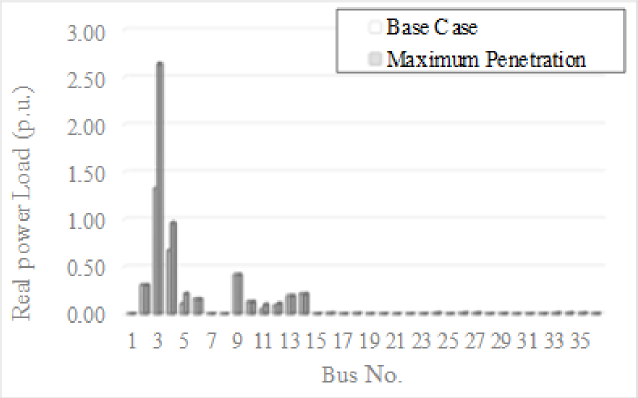

Figure 6 Increase Real Power Load In The Maximum Wind Penetration

IV. *Increase in Active Power Flow.*

The increase in active power flow at maximum wind penetration is shown in Figure 7, with the most overloads occurring in lines 20 and 36.

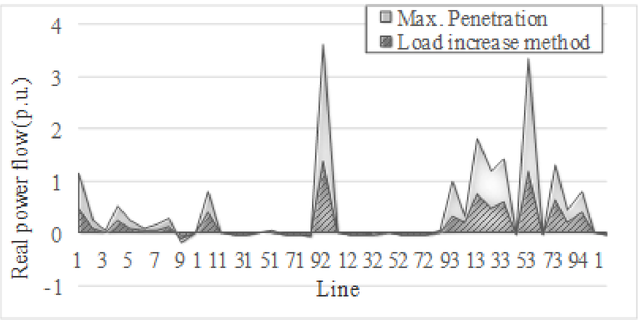

Figure 7 REAL POWER FLOW IN VARIOUS METHODS OF WIND PENETRATION

V. *Voltage and Line Stability Index*

The voltage stability index and line stability factor are expressed as FVSI and LPQ yield values less than one at maximum wind penetration, as shown in Figures 8 and 9, respectively. The two stability indices prove that network stability is maintained at various levels of system power loading. In other words, no lanes are overloaded during maximum operation, and no bus collapses.

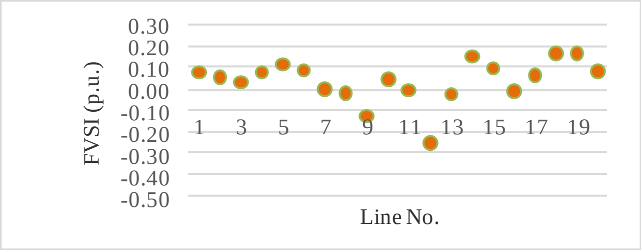

FIGURE 8 FVSI AT MAXIMUM RES PENETRATION

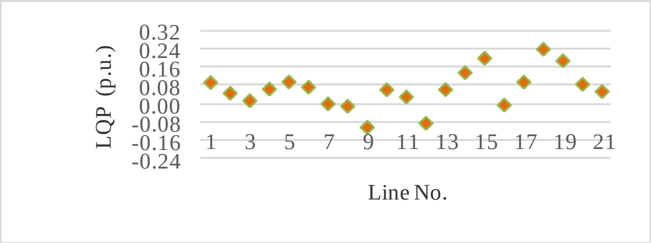

Figure 9 LQP AT MAXIMUM RES PENETRATION

VI. *Small Signal Stability at Maximum RES Penetration.*

Figure 10 depicts the eigenvalues of small signal stability at maximum RES penetration. The Figure shows that the system is stable in the highest RES penetration rate with eigenvalues of less than one. In this Figure, the eigenvalues only plot from 0 to -1.5 due to clarity issues or space limitations.

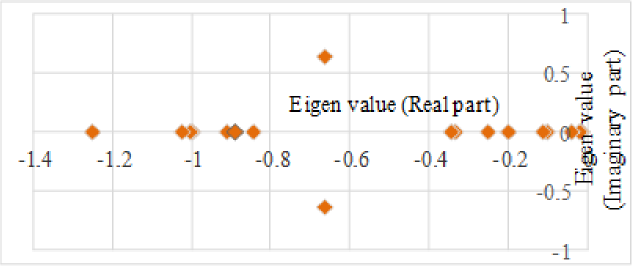

Figure 10 EIGENVALUES AT MAXIMUM RES PENETRATION

CONCLUSIONS

This research has succeeded in elaborating a new method of PSO-based microgrid controller technique to achieve secure maximum RES penetration. PSO-based AI algorithm is applied as a system controller to achieve maximum safe instantaneous wind turbine penetration by considering various security and stability constraints.

The proposed Algorithm explicitly provides the highest load on each bus within the acceptable limits of FVSI, LQP, and small signal stability constraints. The results are promising in the simulations on the modified IEEE 14-bus with a microgrid test system.

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