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Optimal Allocation & Setting of Fuel Cell for Loadability Enhancement in a Wind-PV Integrated System Based On Power System Stability

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ABSTRACT: In this paper, Particle Swarm Optimization (PSO) based technique for the optimal placement & setting of fuel cell in wind integrated power system is developed. By means of fuel cell optimal placement, it is intended to maximize the system loadability while observing the system stability margins viz., small signal stability, voltage stability, and line stability. The impact of optimal integration using PSO algorithm has been analyzed by studying different system parameters like voltage profile, line flows and real power generation. The objective function to maximize is the load power increase at various buses with respect to the base case load. The active power outputs from the distributed generators are adjusted from their base case power outputs in order to supply the additional load and to minimize the disturbance on the conventional generators due to the fluctuating outputs from wind turbine generators. The application of the scheme is illustrated on Central Travancore Practical Grid System. Newton Raphson power flow method and modal analysis are used to quantify the benefits of the proposed methodology. Results present the maximum system loadability in percentage, optimal location and setting of distributed energy resources, maximum safe bus loading beyond which system becomes unstable.

KEYWORDS: Small signal stability, optimal placement, system loadability, distributed energy resources, solid oxide fuel cell.

I. INTRODUCTION

Distributed Generators are gaining widespread applications around the world because of the recent technological advancements in power system towards smart grid technologies. In the current deregulated electricity markets wherein competition is introduced in generation, transmission and distribution, also strongly favours the integration of distributed energy resources in order to maximize the utilization of their resources and facilities for maximizing the profit. Fast depletion of fossil fuels, environmental concerns, advancements in green energy and constraints in erecting additional transmission and distribution lines are also major reason for development of renewable energy systems as viable options for future electricity generation. Distributed generations are an effective method to improve system stability and reliability, reduce transmission losses, increase system loadability, improve system voltage profiles etc.

However the integration and high penetration of distributed generations into the power system poses many issues that need to be addressed carefully. The variations in wind speed and unpredictable solar radiation causes the output powers from wind and photo voltaic systems to fluctuate considerably. With increased size and complexity of modern power system, there are chances of cascaded effect of oscillations from a small disturbance leading to complete system black out. The oscillatory instability is one of the limiting criteria for synchronous operation of distributed generators [1]. Also, the dynamic loadability of a system depends on small signal stability limit [2]. There are other issues like the optimal allocation of distributed generators to extract maximum technical benefits, like higher stability and security margins of operations, better voltage profile, increased loadability, reduced losses.

In this paper, Particle Swarm Optimization (PSO) based technique for the optimal allocation & setting of Solid Oxide Fuel Cell (SOFC) in a wind PV integrated power system is developed. By means of SOFC optimal placement, it is intended to maximize the system loadability while observing the system security and stability margins i.e., small signal stability, voltage stability, and line stability. The objective function to maximize represents the load power increase with respect to the base-case load; equality constraints are the power flow equations; and inequality constraints represents technical limits, such as bus voltage magnitude limits and current flow limits through the branches of the network. In addition, the active power outputs from the distributed generators are also increased/decreased from their base case power outputs in order to supply the additional load and minimize the disturbance on the conventional generators due to the fluctuating outputs from wind turbine generators.

The paper is organized as follows, the first section briefs about distributed generators and optimal DG placement problem. The optimization problem and constraints are formulated in Section 2. Results are detailed in Section 3. Section 4 summarizes the conclusions and major contributions.

II. PROBLEM FORMULATION

A. Maximize The System Loadability Within Stability Margin

The optimization problem to find the optimal location of Fuel Cell DG is formulated as a single objective optimization problem considering the loadability of all buses as given below

$$Maximize\ \ F(x,u) = \sum_{i=1}^{N_b} P_{Li}(\lambda) \tag{1}$$

Subject to the equality constraint

$$P_{Gi} = P_{Li} + V_i \sum_{j=1}^{N_b} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) \ ; i = 1,2,\ldots N_b \tag{2}$$

$$Q_{Gi} = Q_{Li} + V_i \sum_{j=1}^{N_b} V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) \ ; i = 1,2,\ldots N_b \tag{3}$$

where, $P_{Li}$is the total active load at bus i and N_b is the total number of buses in the system.
The inequality constraints $h(\boldsymbol{x},\boldsymbol{u})$are
Apparent power flow limit:

$$S_{ij} \le S_{ijmax} \tag{4}$$

Bus voltage limit:

$$V_{imin} \le V_i \le V_{imax} \tag{5}$$

Slack generator power output limit

$$P_{slack} \le P_{slackmax} \tag{6}$$

$$Q_{slack} \le Q_{slackmax} \tag{7}$$

Wind Power output limit.
The wind power dispatch should not exceed the available wind power from the wind park:

$$P_{wind} \le P_{windmax} \tag{8}$$

$$Q_{wind} \le Q_{windmax} \tag{9}$$

In eq. (1),λ is a load parameter of the system, which maximizes the total power that the network can supply within the system stability margin.
The load factor λ represents the variation of system real & reactive loadsP_{Li} andQ_{Li}, defined as:

$$P_{Li}(\lambda) = \lambda P_{Li}\ ;\ i = m+1 \ldots\ldots, N_b \tag{10}$$

$$Q_{Li}(\lambda) = \lambda Q_{Li}\ ;\ i = m+1 \ldots\ldots, N_b \tag{11}$$

where,*m* is the total number of generator buses, λ = 1 indicates the base load case.

B. Dependent And Control Variables

In eq. (1), **x** represents the dependent variables. The dependent variables in this analysis are slack bus power P_{G1}, load bus voltage$V_{m+1 \ldots\ldots N_b}$, generator reactive power outputs Q_G and apparent power flow S_k; **x** can be expressed as:

$$x^T = [P_{G1}, V_{m+1} \ldots \ldots . V_{N_b}, Q_{G1} \ldots Q_{Gm}, S_1 \ldots . S_N] \tag{12}$$

u represents the control variables. The control variables considered here are generator real power outputsP_G except at the slack bus P_{G1}, generator voltages V_G, and the locations of DER device,L:

$$u^T = [P_{G2} \ldots P_{Gm}, V_{G2} \ldots V_{Gm}, L, \lambda_f] \tag{13}$$

C. Power System Stability Constraints

1) Fast Voltage Stability Index: The safe bus loading of the system is assured by incorporating the Fast Voltage Stability Index (FVSI) proposed by I. Musirin and A. Rahman [8].

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{14}$$

If FVSI≈1.00: bus connected to the line is approaching its instability point. If FVSI≥1.00: one of the buses connected to the line will experience a sudden voltage drop and the bus will collapse due to overloading.

2) Line Stability Index: The line stability index symbolized by L_{mn} proposed by M. Moghavemmi and F.M. Omar [9] is formulated based on a power transmission concept in a single line. The line stability index L_{mn} is given by

$$L_{mn} = \frac{4Q_r X}{[|V_s| \sin(\theta - \delta)]^2} \tag{15}$$

where X is the line reactance, Q_r is the reactive power at the receiving end, V_s is the sending end voltage, θ is the line impedance angle, and $\delta$is the angle difference between the supply voltage and the receiving voltage. The value of L_{mn}must be less than 1.00 to maintain a stable system.

3) Line Stability Factor: System Stability is also assured by Line Stability Factor (LQP) proposed by I. Musirin and A. Rahman [8]. The LQP should be less than 1.00 to maintain a stable system.

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \tag{16}$$

LQP assure that at no level of bus loading the line is overloaded.

III. SIMULATION RESULTS & DISCUSSION

A. System Description

The proposed solution method was tested on Central Travancore Grid (Kerala,India) shown in fig.1. The Central Travancore grid extends over four districts inKerala, viz. Alleppey, Kottayam, Idukki and Pathanamthitta.The model consists of 16 buses, and generating stationsat Idukki and Sabarigiri Hydro Power Plants, KayamkulamThermal Power Plant, Brahmapuram Diesel Power Plant andRamakkelmedu wind farm. The Pallom substation consists ofa 40 MVAR compensator. The highest voltage level in the testsystem is 220 kV at the transmission side which is steppeddown to 110 kV in the substation.

Fuel Cell DG and Solar PV have been connected to different bus and loads are modeled as static loads (constant PQ) withconstant power factor, and increased according to equations (10) and(11). ThekV rating of DG is the kV of the bus to whichit is connected. All the lines of the system except line withgenerators are selected to be the optimal location of theDER.Hence inCentral Travancore System, the locations suitable for fuel cellplacement considered are bus no.s 1, 2, 3, 4, 5, 8, 10, 11, 12,13 and 16. Wind farm consisting of 300 wind turbines and 600 MVA / 220 kV capacity has been connected to Pallom bus as identified using wind farm placement index [5]. The analysis was done using PSAT/MATLAB integrated environment as suggested by F. Milano [10].

B. Results & Analysis

The DG is placed at arbitrary positions and the resultant power flow results are analyzed. The loadability on the buses is increased gradually in such a way that the base case power factor is maintained at all loading points. The bus to which Solid Oxide Fuel Cell (SOFC) is connected is modelled as a $V\theta$bus and all the additional load is supplied by the SOFC resulting in minimum load disturbance on the conventional generators.

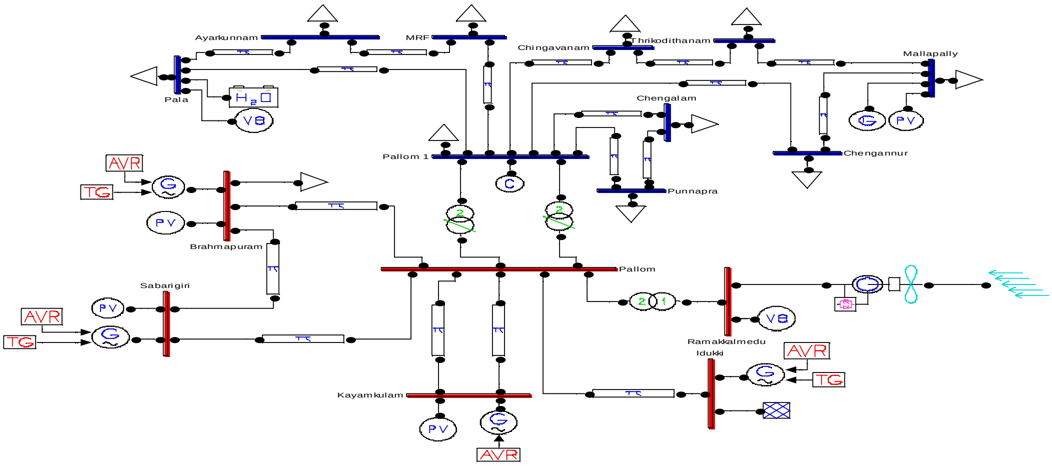

Figure 1. Voltage levels at different buses with and without DG

Using particle swarm optimization algorithm, the optimal location of SOFC for maximum loadability was found to be at bus 1 (Ayarkunnam Bus). The loading of the test system without integrationof SOFC can only be increased to 1.4 times the base caseloading beyond which the system drives into instability and collapses. With the optimal placement and setting of DG the loadability can be increased from the base case loading of 2.63 p.u to 5.03p.u. Total generation and load at maximum system loading is given in Table. I.

Table I
Generation And Load At Maximum System Loading.

System Loadability	P_G	Q_G	P_L	Q_L
Base Case	2.65	0.69	2.63	0.95
At Maximum Loading	5.12	2.09	5.03	1.79
Difference (max load - base load)	2.47	1.4	2.4	0.84

From the table it is obvious that with optimal placement & setting of Distributed Generators (DG), more load demand can be met. In the present work 2.4p.u additional active load could be handled without driving the system into instability i.e. an increase of91.2% loading.

Voltage profile of power system with fuel cell at bus 1 and without DG is compared in fig. 2. It can be seen that at maximum system loading the voltages are maintained within the stipulated limits of 0.9 and 1.1 p.u.

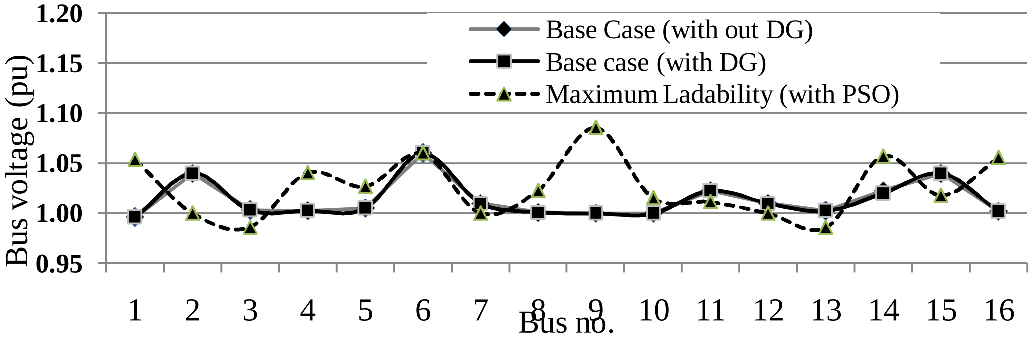

Figure 2. Voltage levels at different buses with and without DG

Fig. 3 shows the Generations at different buses. It can be seen that with optimal placement and setting of fuel cell at bus 1, the conventional generations can be reduced and the whole load disturbance is absorbed by the fuel cell. Bus 2 has the largest load share.

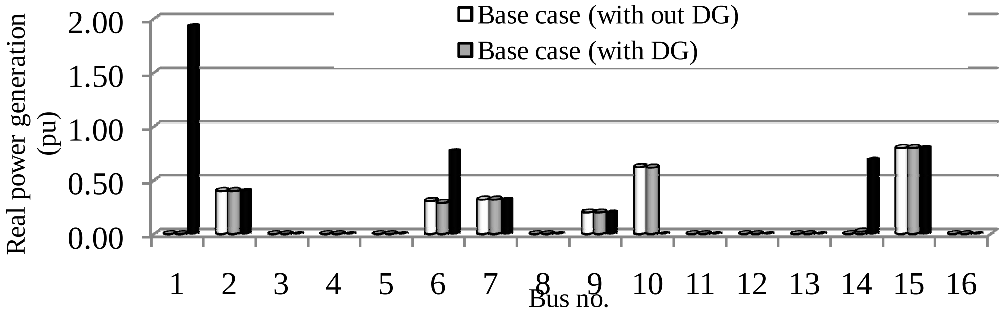

Figure 3. Generations at different buses

Fig. 4 shows the maximum loadability at different buses with & without DG.

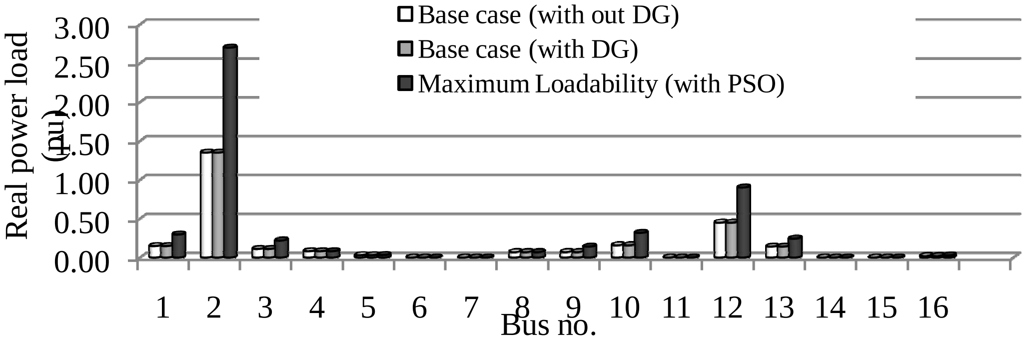

Figure 4. Active loads at different buses

In fig. 5 line power flows with and without DG is shown. The line active power flow increases as the system loading is increased but the stability constraints assures that the increase is within the stability and security margins of the power system.

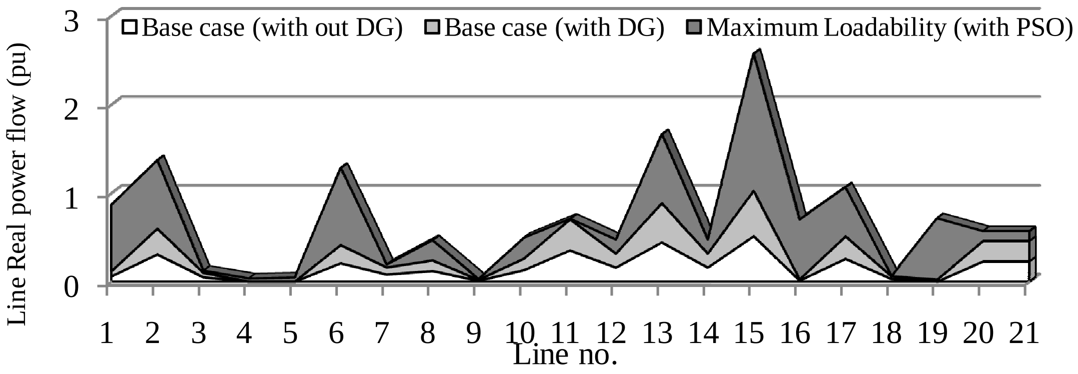

Figure 5. Line Active Power flows.

The stability constraints at the best compromise solution represented by FVSI, LSI and LQP are shown in fig. 6 & fig.7. It can be seen that voltage and line stability indices (FVSI & LQP) are well within acceptable limits. This maintains grid stability at various loading ensuring no bus collapses due to overloading and no line is overloaded under any grid condition.

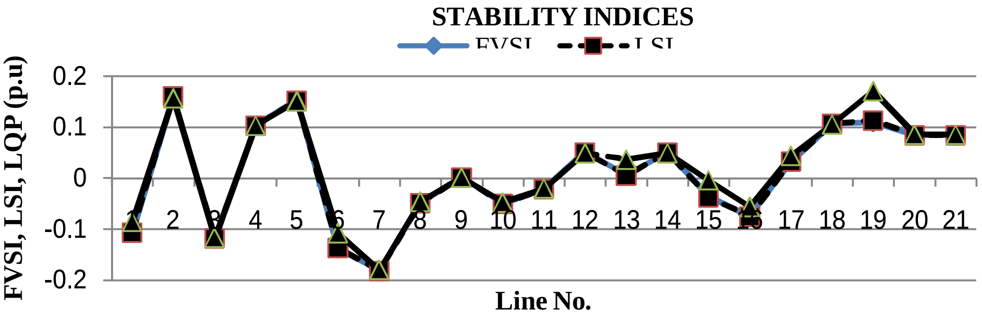

Figure 6. Line Active Power flows.

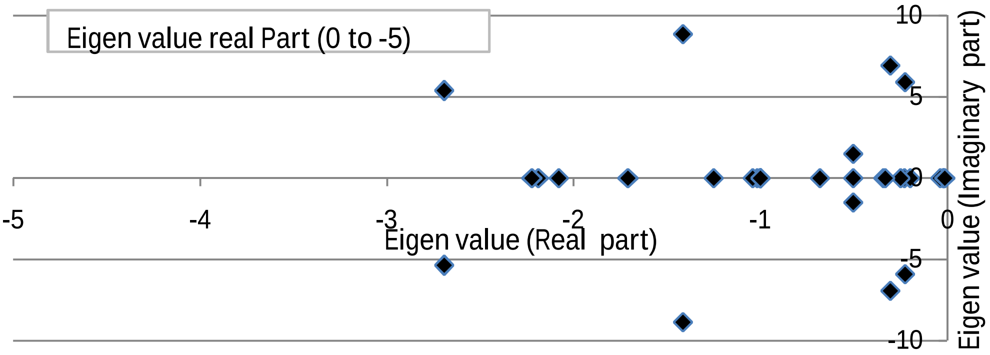

Figure 7. Eigenvalues at maximum loadability

IV. CONCLUSION

In this paper, a new methodology of optimal allocation of distributed energy resources has been proposed to maximize the system loadability by taking into consideration the power system stability and security constraints. It is found that PSO based optimization technique is much better to enable optimal allocation of DG in power distribution system. Incorporation of Fast voltage stability index (FVSI) and Line stability factor (LQP) constraints in the optimization problem ensures grid stability at various levels of system loadability. With optimal placement of DG near to load center the most of the load disturbance can be made to be shared by the DG. The applicability of the proposed scheme was tested on a Central Travancore practical grid system using Newton Raphson power flow method.

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