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OPTIMAL PLACEMENT AND ADAPTIVE CONTROLLING FOR DOUBLY-FED INDUCTION GENERATOR INTEGRATION IN SMALL SIGNAL STABILITY

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ABSTRACT

The optimal location of DFIG improves the small signal stability of wind integrated power system. Also when parameters of PSS are optimized, it helps to improve the small signal stability. In this paper along with optimal placement of DFIG, PSS parameters are optimized which further improves the small signal stability of the power system. The enhancement in small signal stability with optimal location and optimized parameters is shown in this paper using Eigen value analysis. For locating the wind farm in a multi machine system at its optimal position, an Eigen value index (EI) is used. The Eigen value objective function is used for obtaining optimal parameters of PSS. Analysis of the integrated optimization of DFIG location and PSS parameters shows a more effective small signal stabilization in the power system. The placement of DFIG unit at different bus locations reflects in variation of damping factor and movement of the Eigen values. The simulation of a two-area network with four machines, shows that the placement of DFIG unit at bus 4 with optimal PSS parameters resulted into a shift of -0.4 in the real component compared to the previous stabilizing methods. The index (I_{ss}) in terms of damping factor which is a measure of stability, is observed to be improved by 5%when the load is varied by 10%, as compared to the previous individual PSI and WOA methods. Thus the dual optimization, with the use of PSIs for optimal location of DFIG and WOA algorithm for optimal parameters of PSS, used here has proved to be a novel method of improving small signal stability.

Key words: *Small Signal Stability, DFIG Location, PSS Parameters, Eigen Value Analysis, Probability Sensitivity Index.*

1. INTRODUCTION

The biggest challenge the world is facing today is of the increased percentage of emission of greenhouse gases and its consequence of global warming. Also increased prices of traditional sources due to their limited stocks forces adoption of renewable sources like solar and wind. There is a very fast progress in technology of wind power generation and as a result wind power plants are being installed across the world. As the percentage of wind generation in a power system is increasing at a very fast rate, its effect on power system is a concern. The first reason of this concern is the behavior of wind generators which is quite different from traditional synchronous generators. Another reason is unpredictable variable nature of wind. There are many different technologies that are being used, to deal with the variable nature of wind, out of which doubly fed induction generator (DFIG) is the most commonly used generator owing to its many advantages. When such a wind farm is integrated with power system there are different modes of oscillations when subjected to small disturbances. For the best performance of power system, it is essential to know the reasons of these oscillations and also the methods to damp these oscillations. The undamped small signal oscillations put limit on power transfer capability of transmission lines which is not acceptable. In [1] the problem of power system oscillation in the Integrated Nepal Power System (INPS) is examined. In this paper to identify critical modes of oscillations using participation factor and to identify the real area of problem regarding small signal stability in INPS the Eigenvalue analysis is carried out. In [2] small signal

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stability of the Western North American Power Grid with high penetrations of renewable generation is studied where an optimal fixed structure control scheme is used to mitigate the modes. The small signal modes of oscillations which are usually in the range of 0.1 to 0.7Hz are damped by power system stabilizer (PSS) [3]. The power system stabilizer in synchronous generator is copied and introduced in wind turbine controller. The use of PSS has proven beneficial for damping small signal oscillations. Though the use of PSS proven beneficial there is always need to explore the ways and methods to improve small signal stability further as there is always scope to enhance the small signal stability by increasing stability margin. In the research, location of DFIG was fixed and also PSS was tuned only once for stability which puts limit on control operation under dynamic conditions. In [4], PSS was designed to damp small signal oscillations. However the variation of loading condition and network faults were not considered. Application of PSS into power system for small signal stabilization are presented in [5, 6]. To obtain optimized PSS parameters, Grasshopper Optimization Algorithm (GOA) was developed. The approach was developed for a single area system. The optimization was developed with the assumption of fixed DFIG location with no-fault condition.Various methods of PSS design were presented in the past which include a pole placement approach [7], sliding approach [8-10], linear regulation [11], regulated loop technique [12] and a conditional decision logic [13]. The presented approaches were developed for single machine model or multi machine model in a single area system with different loading conditions.

To meet with the increased power demand wind power will have 20% share in power system by 2030 [14]. In this aspect, doubly fed induction generator (DFIG) integrated with wind turbines interfaced with synchronous generators can affect the power flow and system stability. In a multi machine system N-1 oscillations were observed for an N machine system [14]. Due to varying wind input to the DFIG unit, there is a large variation in the output power. In the analysis of small signal stability, DFIG placement in the power system has a critical role. The oscillations are variant with the point of DFIG interface into a power system [15]. The method used a frequency coupling approach for studying stability in the network. However, the stability in terms of damping factor and pole placement were not considered. The variation in the network based on the changing position of generator or control parameter is not considered. Researchers of [16-18] show that an inappropriate location of DFIG increases the factor of instability in the system. The need to analyze the impact of DFIG placement for voltage regulation and system losses in the network was also stated. The location of the DFIG in the analysis of system stability is presented in [19] also. In the presented approach DFIG unit is connected to a weak node and stability is studied. However, the random placement of DFIG and fixed control parameter limits the use of the proposed approach under dynamic conditions. For achieving power system stability for changing operating conditions in [20] a probabilistic approach was proposed. The approach analyzes the effect of dynamic interconnection of DFIG into the power system for system stability. The optimization approach for system stability is developed by Lyapunov method where the range in steady state was assumed. A large range of system parameters has a larger scale of fluctuation resulting in a slower convergence. [21]- [23] presented a method of probabilistic small signal stability using dynamic interface of new energy transformation system. The probabilistic method proposed offers a small signal stability based on the analysis of Eigenvalues by calculating probabilistic density function (PDF). The proposed method has limitation when there is fluctuation in the wind power generation. Also the change in penetration level of wind generation affects the stability of system on greater scale. The analysis of small signal stability for integrated wind power system is outlined in [23]. Eigen analysis based on probabilistic method is proposed for knowing the stability and damping of small signal oscillations. The location of DFIG and the variation of PSS parameters have large impact in the multi area network when load conditions are changing, which is not addressed. In [24] a probabilistic Eigen value sensitivity index (PSI) is presented to evaluate the small signal stability in DFIG integrated power system. The system optimizes the placement of DFIG for minimum deviation and for stabilizing small signal oscillations. The presented approach uses a PSS. The analysis however, doesn't evaluate the stability related to PSS parameters but just related to the PSI parameter in optimal location. In [25] a method for deriving optimal PSS parameters using whale optimization algorithm is developed. The proposed method is developed with the assumption of fixed DFIG unit placement in the network. In the method considered, there is no approach developed, for optimizing the location and PSS parameters simultaneously for stability improvement in a multi area network with DFIG in it. The optimized values of PSS parameters with optimal location of DFIG leads to higher small signal stability. This paper presents an integrated model of optimal location of DFIG and optimized parameters of PSS for maximizing the small signal stability in DFIG integrated power system.

The contributions of the presented work are as listed below

1. PSI for optimal location of DFIG.
2. Optimization of PSS parameters.
3. Dual optimization.
4. Analysis of changing load conditions.

The rest of this paper is presented in six sections. The method of probabilistic Eigen value sensitivity index is outlined in section 2. Section 3 presents the optimization of PSS parameters using Whale optimization algorithm. The dual optimization i.e. optimal location of DFIG with optimized PSS parameters is given in section 4. Section 5 presents the simulation results of developed methods for evaluation of system stability for varying load conditions and different placement conditions. Section 6 presents discussion on the obtained simulation results. Section 7 gives the conclusion of the presented work.

2. PSI FOR OPTIMAL LOCATION OF DFIG

Integration of wind farms to the existing power system has an advantage of supplying additional power using a clean and renewable source of generation. A rapid development in the area of wind power generation and its integration with the power grid is seen in the recent past. When the demand for low emission power generation is increasing, wind power generation seems to be a promising solution. The integration of wind farm has however different stability constraint to be overcome to offer the best performance. Doubly fed induction generator (DFIG) is majorly used in wind power generation due to its higher controllability. The wind turbine converts input wind energy into mechanical energy and feeds it to electrical generator which gives electrical output. The power transformed is given by,

$$Power(P) = \frac{1}{2} p\rho A_r V_w^2 \qquad (1)$$

Where,
p – Power coefficient
ρ – Density of air (kg/m^3)
A_r – Area of turbine blade (m^2)
V_w – Velocity of wind (m/sec)
The transformation of the wind energy into electrical energy is derived by the tip speed ratio $\emptyset$ given as,

$$\emptyset = \frac{R\omega}{V_w} \qquad (2)$$

Where,
R – Turbine radius
The torque (T_q) developed by the system is given as,

$$T_q = (\tfrac{1}{2} p\rho A_r V_w)/\emptyset \qquad (3)$$

When the machine is subjected to small disturbance, the dynamics of generator is presented the swing equation

$$\Delta P_a = \Delta P_m - \Delta P_e \qquad (4)$$

Where, ΔP_m and ΔP_e are the deviations in mechanical input power and electrical power output. From [24], by selecting proper Eigen vector equating phase of ΔP_a to that of λ in the complex plane can make the system more stable by shifting ΔP_a to the left. The relation of angle $\theta$and damping ratio $\varphi$of λ is given by [24] as,

$$\varphi(\%) = sin(\theta)\,\mathrm{sign}(-\alpha) \times 100, \qquad (5)$$

and

$$\theta = sign(-\alpha)\arcsin(|\varphi|) \qquad (6)$$

In a multi machine system with DFIG, the system observes oscillations when subjected to disturbance like load variation or some kind of fault. Power system stability is usually studied in three different forms like voltage stability, frequency stability and rotor angle stability. In rotor angle stability, for a large disturbance, transient stability is to be checked whereas for a small disturbance, small signal stability is important. In small signal stability synchronism is maintained even when the system is subjected to small disturbance for short period of time. For such a short period of time the system can be linearized. The stability issue in the network can be local or global. Global instability is seen under different interconnected generator units. The oscillations in the range of 0.3 to 0.8 Hz are the global mode of oscillations whereas oscillations in the range of 1 to 3Hz are called as local mode of oscillations. The unstable system may have non oscillatory boundless response or response in the form of oscillations of increasing magnitude. The non-linear power system can be represented by a linear system for a small disturbance. To analyze the small signal stability of the wind integrated power system, method of Eigen analysis is used. Eigen value can be a complex number, where the real part defines the damping factor and the oscillatory frequency is defined by the imaginary part. A larger negative value of the real component reflects in higher damping which is responsible for faster oscillatory suppression.

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For an M-machine network, M-1 oscillations are observed. The placement of the wind farm has a direct impact on the system. The location of DFIG is also found to be important from system stability point of view. This fact has led to the development of method for optimization of DFIG location in a two area network to maximize the small signal stability. In optimization of the DFIG placement in [24] a probability based approach termed 'probabilistic Eigen value sensitivity index' (PSIs) is proposed.
When a power system works normally, the amount of power generated, amount of power consumed, Eigen values of system are the random variables. The samples during system operation decide the statistical particulars of the probabilistic data. The probabilistic Eigen value analysis is helpful in knowing the distributions that are probabilistic and also in probabilities of stability of Eigen values.
For a given Eigen value $\lambda = \sigma \pm j\omega$, the sensitivity of damping factor indicates location of generator with respect to controller parameter. Hence the probabilistic sensitivity index outlined in [24] where the real part of an Eigen value and the damping ratio with respect to controller parameter indicate strong and weak correlation of generators' Eigen values and this fact can be used for DFIG location and selection of parameters under probabilistic conditions. The PSI is given by,

$$PSI_\sigma = \frac{\partial\sigma}{\partial G_m}_{G_m=0} \tag{7}$$

$$PSI_\varphi = \frac{\partial\varphi}{\partial G_m}_{G_m=0} \tag{8}$$

The frequency of oscillation is given as,

$$f = \frac{\omega}{2\pi} \tag{9}$$

and the damping factor φ is given by

$$\varphi = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \tag{10}$$

The multi machine system described by the linearized state space model is given by,

$$\check{S} = AS + BZ \qquad Y = CS \tag{11}$$

And the residue component is given by,

$$R_i = C\vartheta_i\gamma_i^T B \tag{12}$$

Where,
$\vartheta_i$and γ_i represent the left and right eigenvectors of the system matrix A. For single variable feedback, the sensitivity is equal to the residue, if q stands for a PSS gain, the residue of the open-loop system given by equation (12) can also be obtained from the Eigen value sensitivity $\partial\lambda_k / \partial q_{q=0}$ of its closed-loop system [24]. So for a PSS gain q, the RI of the system is derived from the Eigen value sensitivity given by,

$$\frac{\partial\sigma}{\partial q}_{q=0} \tag{13}$$

Here, the probabilistic sensitivity indices can be used for the placement of the DFIG and for improving the small signal stability.

3. WHALE OPTIMIZATION ALGORITHM (WOA)-BASED POWER SYSTEM STABILIZER

In recent past, for optimization of PSS parameters for small signal stability, a bio inspired whale optimization approach (WOA) is presented in [25]. An Eigen value based objective function is used to implement design of PSS. The presented whale optimization algorithm is simpler in computation where two objective functions are tuned based on the Eigen value. The proposed approach is developed for small signal stability in a multi machine system and a search method for random distribution is performed.
The WOA optimizes the PSS parameters. The optimization process is started by selecting parameters of PSS as control variables and selecting their minimum and maximum values. The following expression [25] gives the initial solutions which are randomly generated

$$C_{mn}^0 = C_m^{min} + rand(C_m^{min} - C_m^{max}) \tag{14}$$

Here, C is the control parameter and *min* and *max* are the lower and upper limits of the control parameters. 'm'is the number of control variables and 'n' is the population size. Two objective functions one for real part of Eigen value and other for damping factor are formulated and then combined to get combined objective function. Then WOA is used to imitate the process of hunting agent updating. In the process of optimization, parameters of PSS are used as hunting agents. After identifying target location the mechanism to reach the prey is used by hunting agent for posture updating. The algorithm assumes present solution to be the best solution as the best solution is not known and position is updated using:

$$U = |V.I \times I^*I(t)| \tag{15}$$

$$I(t+1) = I^*(t) - A.U \tag{16}$$

where, U is the distance of the updated value with the target value.

V and A are the coefficient vectors and t is the present iteration. I^* is the present updated value measured at time t. I is the position vector. The optimization process is iterated for t times with the assumption of each updation to be optimal one. The iteration converges when the error is minimum or the iteration count terminates.

In [24] optimal location of DFIG is selected by using PSIs. Optimal location of DFIG in the network is obtained by monitoring the deviation in the real component of Eigen value. The deviation is controlled by the controller of generator with PSS. The parameters of PSS will decide the generation of control signal. The drawback of the existing PSI approach is the fixed values of PSS parameters. It is known from [25] that variation in PSS parameters has impact on the stability. Hence, the PSS parameters should be tuned to optimal values for improving the stability. The optimization of PSS parameters is defined in [25], where a heuristic WOA approach for optimization of PSS parameters is given. The optimization of PSS parameters is carried out with the assumption of fixed position of DFIG in the network. The two existing methods for improvement in small signal stability illustrate that the varying location of DFIG and varying PSS parameters of the controller have varying effect on the stability of the system. However, the integrated approach of optimizing both location and PSS parameters simultaneously for DFIG is not developed. Hence there is a need to develop an approach to optimize both the parameters simultaneously to improve stability under varying conditions. The drawback of fixed positioning of DFIG in [24] and fixed values of PSS in [25] is overcome by an integrated approach proposed which derives the best location of DFIG unit with best PSS parameters for maximizing small signal stability.

4. DUAL OPTIMIZATION

In the placement of DFIG the PSI parameter has a crucial role, which is based on the derivative of the real part and damping factor of the Eigen value. Interface of controller unit in a DFIG is shown in figure 1. The small disturbances on power system cause small signal oscillations and to damp these oscillations PSS is used as an additional controller. In the selection of PSS location eigenvectors are used considering the participation factor (PF) and residue index (RI). When PSS is used for damping small signal oscillations there are two factors which should be given due consideration viz. its location and its parameters. The dual optimization can be expected to offer maximum stability.

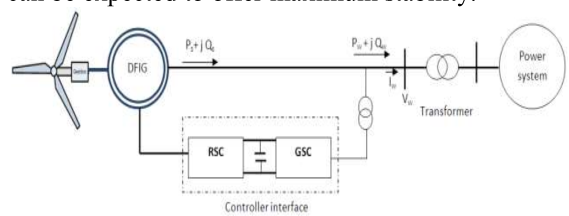

Figure 1: Controller interface in DFIG unit

The three constituting parts of PSS are phase compensator, wash out filter and gain. Each block has its contribution in the damping performance. The phase compensator is used for lag-lead compensation. The washout filter is used for high pass filtration and gain block offers a required gain for damping of oscillations in the system. The transfer function of the PSS is given by,

$$O_s = G_{Pss} \frac{sT_w}{1+sT_w} \left[\frac{(1+sT_1)(1+sT_2)}{(1+sT_3)(1+sT_4)}\right] \Delta\zeta_i \qquad (17)$$

where, O_s is the output of PSS. T_w is the washout time constant and T_1-T_4 are the phase compensating time constants and $\Delta\zeta_i$ is the deviation in speed of the machine under consideration. In optimizing the PSS parameters an Eigenvalue based objective function is presented in [25]. The approach defines the objective functions for real part of Eigen value and damping factor given as,

$$\min(J_a) = \sum_{i=1}^{L} \sum_{\alpha_i \geq \alpha_0} (\alpha_0 - \alpha_i)^2 \qquad (18)$$

and

$$\min(J_b) = \sum_{i=1}^{L} \sum_{\varphi_i \geq \varphi_0} (\varphi_0 - \varphi_i)^2 \qquad (19)$$

Where, L is the number of the possible loading conditions considered. α_i represents the real part of the i^{th} Eigen value and α_0 is the constant whose expected value is taken as -1.5. When objective function given by equation (18) is used for designing PSS, there will be improvement in the system eigenvalues which are badly damped, moving them away from imaginary axis in the left half plane. In equation (19) φ_i is the damping ratio of i^{th} Eigen value and φ_0 is a constant whose expected value is taken above 0.3. When objective function given by equation (19) is used to design the PSS then there will be improvement in the damping ratio of oscillating modes which are lightly damped. To achieve both the improvements the two objective functions are combined and is given by equation (20)

$$J = J_a + kJ_b$$

$$J = \sum_{i=1}^{L} \sum_{\alpha_i \geq \alpha_0} (\alpha_0 - \alpha_i)^2 + k \sum_{i=1}^{L} \sum_{\varphi_i \geq \varphi_0} (\varphi_0 - \varphi_i)^2 \quad (20)$$

Where k is the weight factor used to balance the effect of J_a and J_b whose value is taken as 10.

The optimization process is started by selecting parameters of PSS as control variables. Also their minimum and maximum values are decided so that the range gets selected. The starting solutions are generated randomly by using the expression given as:

$$V_j = V_{min} + rand(V_{min} - V_{max}) \quad (21)$$

Where, V_j is the control variable which is processed for a random value distribution of V_{min} to V_{max}, $j=1, 2,\ldots.p$, where p indicates the selected control variables. Rand function defines randomly scattered initial values in the range of 0 and 1. Then WOA is used to imitate the process of hunting agent updating. In the process of optimization, parameters of PSS are used as hunting agents. After identifying target location the mechanism to reach the prey is used by hunting agent for posture updating. As the best solution is not known, the algorithm assumes the present solution to be optimum solution and position is updated using

$$U(t+1) = U^*(t) - A.D \quad (22)$$

Where, U is the value of current update, $U^*(t)$ is the optimum values obtained for iteration t. D is the distance vector of the limiting value and the random parameters. A is the matrix representing the coefficients given by,

$$A = 2a.r - a \quad (23)$$

Where A is a random value in the process of optimization and r is any number that can have value from *0 to 1*.In every iteration, for each hunting agent the values of 'A' are updated.

The iterations are performed for given loop for optimizing the cost function and the optimized parameters of PSS are obtained. With the optimized PSS parameters if DFIG is placed at its optimal position, that results into finer stabilization of small signal stability. The PSS is usually placed in rotor side controller. For selecting the site of DFIG, residue index and participation factor have been used [24].A linearized multi machine system is described by equation (11). Equation (12) gives calculation of residue matrix for a particular mode 'i'. The transfer matrix of PSS which is included in the control circuit, for the closed loop system

$Z = F(s, q)\ Y$, and the coefficient matrix becomes

$$K = A + Bf(s,q)C \quad (24)$$

As a result, with λ_i as an Eigen value, its sensitivity in respect of q which is a feedback parameter, is given as

$$\frac{\partial \lambda_i}{\partial q} = \vartheta_i \frac{\partial K_i}{\partial q} \gamma_i \quad (25)$$

The residue is equal to sensitivity when only one variable is fed back, if PSS gain is given by q,the Eigenvalue sensitivity

$$\partial \lambda i / \partial q_{\ q=0}$$

is the residue of the open loop system. The residue component is given by

$$R_i = C\vartheta_i \gamma_i^T B$$

A two-area network with four synchronous generators (SG) is shown in figure 2. The optimization problem is developed here for a multi machine model in a two area system, where two different cases are considered for the analysis of optimization problem

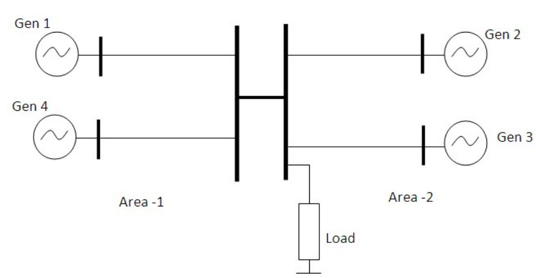

Figure 2: Layout of two area four machine system

The first case is a random placement of the DFIG into the system and observing the stability criterion using PSS. In the second case the dual optimization i.e. optimization of PSS parameters and optimization of DFIG location is used for stability analysis. The placement of DFIG is shown in figure

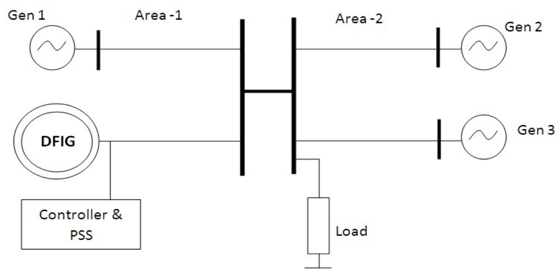

Figure 3: Placement of DFIG unit in the power system

The flowchart of overall operation of the optimizing approach is presented in figure 4

Table 1: DFIG parameter for simulation

Variable	Values
Rated power (MW)	85
Rated Voltage (KV)	18
R_s (pu)	0.0049
R_r (pu)	0.0055
J (kg m^2)	2.84×10^5
L_{lr} (pu)	0.0996
L_m (pu)	3.935
P	2
D (pu)	0.01

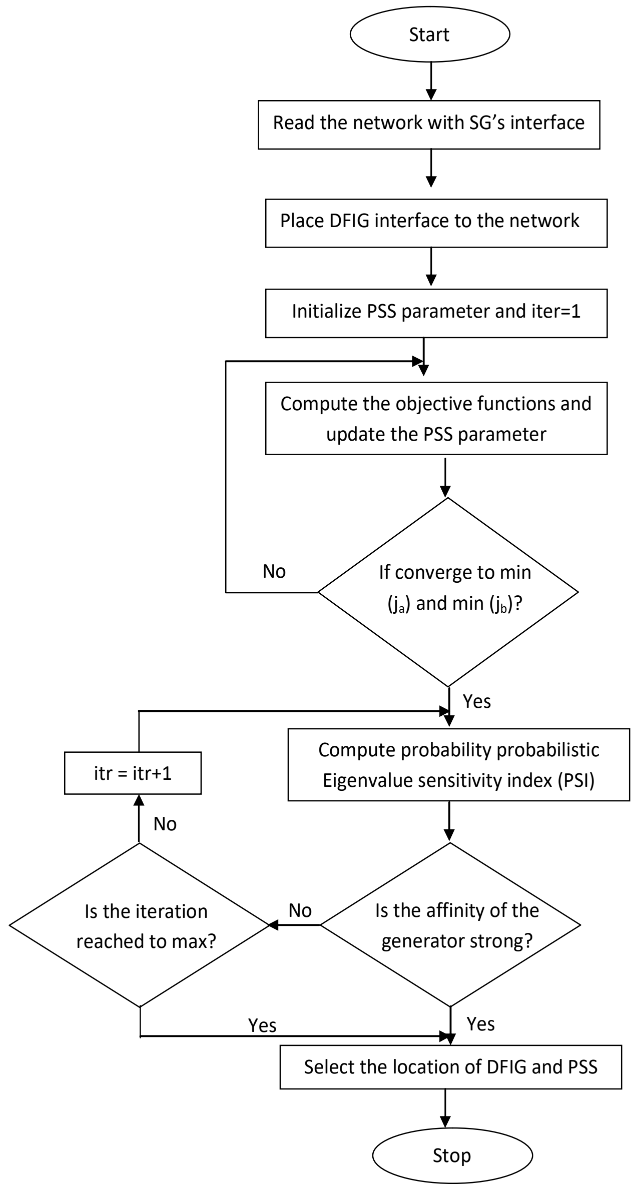

Figure 4: Flowchart of overall operation

Analysis of the proposed approach is done for a four machine two area system, with DFIG replacing the generator in the network. The system consists of the synchronous generators and wind farm having DFIGs. The simulation is developed for DFIG of the rating of 85MW with load of 100MW on the system. The simulation of the power system is developed for the stability study using Eigen value analysis. The wind farm is defined with DFIG having parameters listed in table 1.

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The analysis of the placement of DFIG is done by changing location of DFIG. The system is evaluated using Eigen value analysis, giving the damping factor and the frequency. Also the parameters of PSS are optimized. The parameters of PSS considered are listed in table 2.

When DFIG is placed at different buses the variation in Eigen values is shown in table 3.

5. Simulation Results

Table 2: PSS parameter in DFIG placement [25]

Parameter	Value
K	50
T_1 (s)	0.1
T_2 (s)	0.1
T_3 (s)	0.04
T_4 (s)	0.04

Table 3: Observation for stability parameter for DFIG with changing location

DFIG placement Bus	PSI [22]			WOA [23]			PSI-WOA		
	λ	φ	f (Hz)	λ	φ	f (Hz)	λ	φ	f (Hz)
01	-0.211±j7.514	2.81	1.195	-0.669±j0.663	0.711	0.105	-2.492±j6.361	39.47	1.013
02	-0.207±j7.518	2.76	1.196	-1.133±j0.122	0.538	0.019	-2.391±j6.368	39.56	1.014
03	-1.327±j11.60	11.37	1.846	-2.062±j0.135	0.998	0.021	-2.360±j6.370	39.58	1.012
04	-1.351±j11.62	11.55	1.849	-2.021±j0.141	0. 980	0.022	-2.337±j6.372	39.60	1.011

It is observed, when DFIG is located in bus 4, there is highest oscillatory suppression. A small signal stability index (Iss) is used for defining the system stability by correlating the damping parameter before and after replacement. The Iss parameter is defined as,

$$I_{ss}(\%) = \sum_{k=1}^{n} \frac{\varphi_k - \varphi_{k0}}{\varphi_{k0}} \times 100, k = 1,2,3, \dots n \quad (26)$$

Where, φ_{k0} is the damping parameter before DFIG integration. The parameters for PSS under different loading condition, with a variation of 10%, is given in table 4.
The selection of DFIG location with the optimized PSS parameters is simulated. The values for the Iss for the maximum stability is presented in table 5 with the optimal location and optimized PSS parameters.

Table 4: PSS parameter optimized for different loading condition

Method	**Loading scenario**	**Gsss**	$\mathbf{T_w}$	$\mathbf{T_1}$	$\mathbf{T_2}$	$\mathbf{T_3}$
WOA[23]	1	42.33	0.1	0.105	0.024	0.0481
	2	43.15	0.1	0.129	0.031	0.0601
	3	39.789	0.1	0.012	0.011	0.034
	4	41.021	0.1	0.112	0.021	0.0487
PSI-WOA	1	44.24	0.1	0.119	0.032	0.051
	2	46.33	0.1	0.132	0.044	0.063
	3	42.765	0.1	0.021	0.016	0.039
	4	44.115	0.1	0.165	0.029	0.049

Table 5: Values of Iss for maximization of stability

Loading scenario	PSI [22]	WOA [23]	PSI-WOA
1	9.15	11.73	14.23
2	6.77	8.11	9.611
3	3.23	4.65	8.964
4	2.87	3.34	7.687

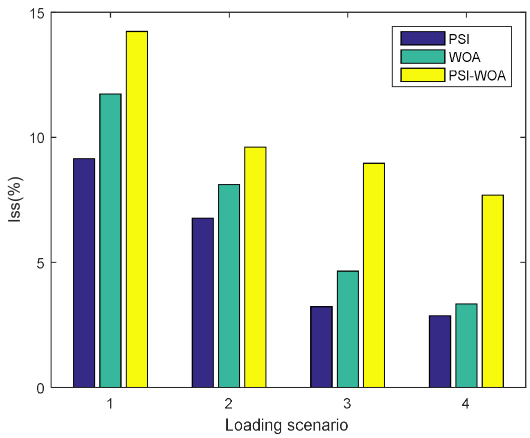

Figure 5: Comparative plot for Iss with different methods

The stability index calculated for different methods given in figure 5 shows a stability of about 5% higher in comparison to the other approaches. The method is improved by the selection of DFIG location using PSI and optimizing PSS parameter using cost optimization. The results obtained indicate the location of DFIG unit at bus 2, 4 is the best suitable placement and offers maximum small signal stability. The placement is evaluated for the different loading conditions and the values of damping factor and frequency based on Eigen value analysis is listed in table 6.

Table 6: Stability parameters for different loading conditions with PSI-WOA for different bus placement

DFIG Placement	Bus-2 placement			Bus-4 placement		
Loading case	λ	φ	f (Hz)	λ	φ	f (Hz)
01	-2.875±j6.186	41.13	1.765	-2.992±j5.242	43.01	1.566
02	-2.488±j6.543	41.63	1.298	-3.413±j5.522	43.44	1.765
03	-2.421±j6.654	40.23	1.176	-2.891±j5.632	42.21	1.772
04	-2.401±j6.665	41.96	1.154	-2.974±j5.513	44.67	1.543

It is observed that DFIG with the selected location and optimized PSS parameters result into higher small signal stability compared to the other approaches. Dual optimization i.e. optimization of location of DFIG using PSI and optimization of PSS parameters using cost optimization results in a faster damping improving Iss parameter. For different loads the Eigen values are obtained. The change in real part of Eigen value, damping factor and frequency of oscillations are presented in Table 6.

5. DISCUSSION

The change in location of DFIG changes the performance in terms of the stability. With the change in location of DFIG there is variation in the Eigen values. The Eigen value analysis of the system shows a shift of real component to more negative region implying a more stable operation. As given in table 3, when DFIG is placed in bus 4, the integrated approach of PSI-WOA obtains -2.337 real component compared to -2. 102 and -1.351 for WOA and PSI method. The proposed approach of PSI-

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WOA attains 0.4 and 0.32, higher negative real component compared to PSI and WOA approach respectively. The same trend can be observed from table 3 when DFIG is placed in bus 1, bus 2 and bus 3.The damping factor is observed to be increased with changing DFIG location where bus 04 placement observes to have higher damping. The optimal location of DFIG is derived using the PSI approach for improvement in small signal stability. However, the PSS parameters are also important in the stability performance. The PSS parameters are optimized using WOA method. These are the two different methods in which at a time only one optimization is possible; either optimization of PSS location or the optimization of PSS parameters, which results in the improvement of small signal stability to a small extent, however the dual optimization is carried out here using the integrated PSI-WOA approach. This approach optimizes the placement and finds the best DFIG location with optimal PSS parameters simultaneously. Such dual optimization results into further improvement in the stability and damping performance of oscillations. The Iss parameter is considerably improved by 5 and 4 units compared to PSI and WOA methods respectively. The results show the variation of load where with increase in load, the Iss decreases. The heavy load has a larger oscillations which decreases the damping ratio, however the proposed integrated model shows an increase in Iss compared to PSI and WOA methods. For optimal PSS parameters, the optimal placement of DFIG is made, in consideration with load variation. Table 6 gives the stability parameters and damping performance of the proposed PSI-WOA approach for varying DFIG placement with increase in load. The DFIG placement at bus 4 is found to have a higher stability performance for any load. An increase of 0.5 negative value in real component and 3 units in damping factor is observed by the proposed PSI-WOA approach for DFIG placement on bus 4. Such an improved performance though desired at all other buses, could not be achieved to that extent. In [24] PSI's are calculated to find optimal location of DFIG. In [25] WOA approach is used for obtaining optimized parameters of PSS. Here an attempt is made to improve small signal stability further by optimizing PSS parameters for optimal position of DFIG.

6. CONCLUSION

In this paper considering stochastic uncertainty introduced due to integration of wind farms, probabilistic Eigen value sensitivity indices are obtained. The indices are used for the selection of wind farm location. The selection of site of DFIG and its controller with PSS is indicated by PSIs as in [24]. This index helps to get the optimal location of DFIG. The PSIs indicate correlation of Eigen values of generators and can be used for location of DFIG.The synchronous generator which is strongly correlated is replaced by DFIG. The design of PSS using conventional techniques for the multi-machine power system, and operating at variable load conditions is a complex process [25]. For solving complex problems PSS is designed using different algorithms and these algorithms have shown their effectiveness. A Whale Optimization Algorithm (WOA) is one such effective algorithm implemented in [25] in which the PSS design methodology is implemented using an Eigen value (EV)-based objective function. The algorithm helps to know the solution that is global and the best by maintaining a very good balance between exploration and exploitation stages and also requires less parameters for control. Also convergence is fast. In this paper PSS parameters are optimized using WOA algorithm for optimized location of DFIG which is obtained using PSIs. The presented approach of dual parameter monitoring offers an optimal location of DFIG placement with optimized parameters of PSS, improving small signal stability of multi machine two area system. The effect of changing load on the system stability is seen. For compensation of demanded load the existing power system is supported by DFIG based wind farms. However, the optimal location is desired for offering highest stability in the network. The small signal variations observed in the DFIG interfaced network is minimized by the PSS integrated to controller unit of the DFIG. The performance of controller is decided by the different parameters of PSS. The two different problems are addressed here, firstly finding optimal location of DFIG and secondly optimizing the parameters of PSS. Two cost functions for minimization of deviation of real parameter and minimization of varying damping factor is proposed to derive optimal location and Whale optimization algorithm is proposed for optimization of PSS parameters. The proposed integrated approach for a two area four machine network is simulated with three synchronous generators and one -DFIG unit. The placement of DFIG unit at bus 4 resulted into higher damping value of 39.60 compared to other three bus locations. The PSS parameters computed by the integrated (PSI-WOA) approach for the DFIG unit at bus 4 obtains the small signal stability index (I_{SS}) of 7.687 compared to 3.34 and 2.87 for WOA and PSI respectively at higher load in the network.

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The optimal placement of the DFIG with the optimized PSS parameters show a higher small signal stability as seen from the obtained damping factors ranging from 43.01 to 44.67 for different load conditions compared to 39.60 with only PSI optimization. In the past many algorithms are used for optimization of PSS parameters and different methods are used for finding optimal location of DFIG. In this paper a novel method of both optimizations i.e. optimizations of PSS parameters and optimal placement of DFIG are simultaneously implemented for enhancement in small signal stability. The observations mentioned tell the significance of optimizing location and PSS parameters simultaneously, which is observed to offer more stability for different load conditions in the network.

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