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Distributed Slack Bus Model for a Wind-Based Distributed Generation using Combined Participation Factors

Peter Musau Moses[1], Dr. Nicodemus Abungu Odero[2]

[1]*Post Graduate student,* [2]*Senior Lecturer, Department of Electrical and Information Engineering, The University of Nairobi-Kenya, P.0 Box 30197-00100 GPO*

Abstract **- With the increased penetration of distributed generation into the power distribution system, the traditional load flow analysis that assumes a single slack bus has become impractical. The existing literature focuses on slack bus placement taking only real power losses into place.However with increasing need of reactive power in maintaining voltage stability at the consumer end; reactive power generation management cannot be ignored any further. Thus a distributed slack bus model taking into consideration both real and reactive power losses is of paramount importance. The wind based doubly fed induction generator is an attractive option for both real and reactive power loss compensation since it is economically attractive, can be grid connected and it has the capability to generate and absorb reactive power. A distributed slack bus model using combined participation factors is developed in this paper to distribute the slack(real and reactive power losses).The combined participation factors are formulated using the method of Lagrange multipliers and the distributed slack bus model employs a Genetic Algorithm of a Newton Raphson Solver.**

Keywords **- Combined participation factors, Distribution System, distributed generators (DGs), doubly fed induction generator (DFIG), Participation factors.**

I. INTRODUCTION

Load flow analysis is a basic tool for power system studies. In a traditional power flow with a single slack bus model, one generator bus is selected to be the voltage phase angle reference and this is assumed to balance the real power mismatch due to uncertain system real power loss. However, there is no slack bus in actual power systems especially with distributed generation. Thus, single slack bus model significantly distort computed power flows.

For many years, power systems have been vertically and centralized operated systems. The large hydro, thermal and nuclear power plants generate most of the power due to their scale and economic merits. The electric power is transmitted and distributed to consumers over long distances at different voltage levels. The centralized and hierarchical control is applied to allow real time monitoring and control of the power system.

However, the existing power system structures are changing due to [1]: geographical and environmental constraints, Stability and security problems of large power generation plants, rapidly growing demand related to investment, privatization of power generation, deregulation, competitive energy markets and emergence of advanced generation techniques with small ratings employed resulting in environmental benefits and increased profitability.

Consequently, in the recent years, deregulation and liberalization of the energy market, increasing petroleum fuel prices and associated environmental concerns has attracted the attention of researchers/developers to incorporate distributed generation (DG) in distribution system planning. DG is a relatively small power generation source (from a few KW up to 10 MW), usually, connected in the power distribution network or at the consumer side for the purpose of reducing power losses, improving voltage profile and power quality, peak shaving, eliminating the need of reserve margin with improved environmental concerns and increasing the network capacity. The only problems of DGs include the stability issues, complex protection strategies and the islanding problems [2]. However, the major driving forces for the increasing penetration of DG in distribution system are the viable technical, economical and environmental benefits [3].

Further, the fluctuating global fuel prices, concerns with the depleting fossil fuel reserves and apprehension relating to climate change has resulted in an increasing focus on renewable sources to satisfy rising global energy requirements. Amongst the available renewable sources of energy, wind and hydro are the most feasible for utility scale power generation. With a majority of the hydro reserves around the world reaching the maximum capacity in terms of available power, there is an increasing shift towards wind power generation to satisfy the need of a clean renewable source [4], [5]. The year 2008 was a record year for wind generation in the United States with a total increase of 8,360 MW which is 50% of the total wind power capacity at the end of 2007 [6].

Wind energy accounted for 42% of the total new capacity added. In 2008, the United States overtook Germany to become the country with the largest installed wind power capacity in the world. The total wind power capacity of the United States is at 25,170 MW [7]. Federal policy in the form of production tax credits and state regulations in the form of renewable portfolio standards (RPS) [8] have contributed to encouraging the development of wind generation in the United States [9]. Over 25 states have accepted RPS by requiring a substantial contribution from renewable sources of energy to their power generation portfolio [10]. As a result wind energy is gaining interest now-a -days as one of the most important renewable sources of energy due to its eco-friendly nature. But the major disadvantage lies in variable speed wind generation.

Doubly Fed Induction Generator (DFIG)

This paper will focus on the formulation of a distributed slack bus model of wind-based Distributed Generators which are promoted and motivated by environmental considerations[11].Wind turbine generators can be classified into three as [12,13,49]:Induction Generators(Doubly Fed Induction Generator-DIFG,Singly Fed Induction Generator-SFIG,Squirrel cage Induction Generator-SCIG),Permanent magnet Alternators (Permanent magnet Synchronous Generator-PMSG) and Brushed DC Generators.In this paper, a Grid-connected variable speed DFIG[14] because it is commercially viable and frequently used in grid connected mode[15].

The Doubly Fed Induction Generator is shown in figure 1 [16]. It consists of a wind turbine that is connected through a gear train to the rotor shaft of the induction generator. The rotor terminals of the induction machine are connected to the four-quadrant power electronic converter capable of both supplying real and reactive power from the grid to the rotor as well as supplying real and reactive power from the rotor to the grid [17].

The converter consists of two separate devices with different functions, the generator side converter and the grid side converter. The generator side converter controls the real and reactive power output of the machine and the grid side converter maintains the DC link voltage at its set point. These converters are controlled respectively by the Generator side controller and the Grid side controller. The DFIG also has a wind turbine control that maximizes the power output from the turbine through pitch control and sends this computed maximum real and reactive power output to the converter. The Power electronic converter is connected to the grid through a transformer that steps up the voltage to the grid.

The stator side of the induction generator is also connected to the grid through a step up transformer.In case the system voltage and power reliability requires that additional reactive power be injected, a static compensator (STATCOM) may be connected at this point of interconnection.

Objective

Thus,the main objective of this paper is to formulate combined participation factors for a DFIG taking into consideration both real and reactive powers and their corresponding losses.In this case the participation factors are formulated using the method of langrage multipliers. Then a distributed slack bus model for the distribution system with DFIG will be done using a Genetic Algorithm with a Newton Raphson Solver.

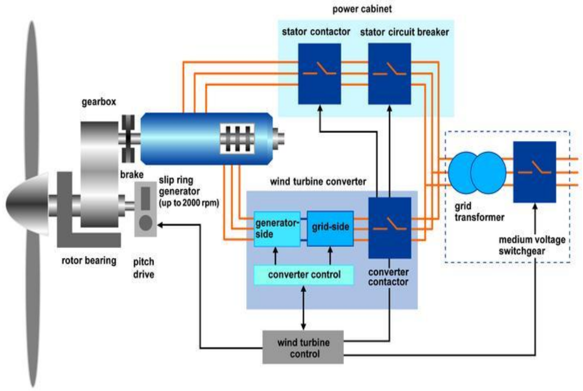

Figure 1:DFIG Schematic Diagram[16]

A. DFIG Reactive Power And Voltage Control

Voltage control and reactive-power management are two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission distribution power networks. On an alternating-current (AC) power system, voltage is controlled by managing production and absorption of reactive power. There are three reasons why it is necessary to manage reactive power and control voltage[44]. First, both customer and power-system equipment are designed to operate within a range of voltages, usually within±5% of the nominal voltage. At low voltages, many types of equipment perform poorly; light bulbs provide less illumination, induction motors can overheat and be damaged, and some electronic equipment will not operate at. High voltages can damage equipment and shorten their lifetimes. Second, reactive power consumes transmission, distribution and generation resources.

To maximize the amount of real power that can be transferred across a congested transmission interface, reactive-power flows must be minimized[57,58]. Similarly, reactive-power production can limit a generator's real-power capability. Third, moving reactive power on the transmission system incurs real-power losses. Both generation capacity and energy must be supplied to replace these losses[50,51].

Further,voltage control is complicated by two additional factors[58]. First, the transmission and distribution system itself is a nonlinear consumer of reactive power, depending on system loading. At very light loading the system generates reactive power that must be absorbed, while at heavy loading the system consumes a large amount of reactive power that must be replaced. The system's reactive-power requirements also depend on the generation and transmission configuration[59]. Consequently, system reactive requirements vary in time as load levels and load and generation patterns change. The bulk-power system is composed of many pieces of equipment, any one of which can fail at any time. Therefore, the system is designed to withstand the loss of any single piece of equipment and to continue operating without impacting any customers. That is, the system is designed to withstand a single contingency. Taken together, these two factors result in a need of a dynamic reactive-power requirement[56]. The loss of a generator or a major transmission line can have the compounding effect of reducing the reactive supply and, at the same time, reconfiguring flows such that the system is consuming additional reactive power.Since reactive power loss has not been included in the existing load flow studies,reactive power generation ,injection , absorption and loss cannot be managed,hence voltage instability.

At least a portion of the reactive supply must be capable of responding quickly to changing reactive-power demands and to maintain acceptable voltages throughout the system[50,51]. Thus, just as an electrical system requires real-power reserves to respond to contingencies, so too it must maintain reactive-power reserves. Loads can also be both real and reactive. The reactive portion of the load could be served from the transmission and the distribution system. Reactive loads incur more voltage drop and reactive losses in the transmission and distribution system than similar-size (MVA) real power loads.

Vertically integrated utilities often include charges for provision of reactive power to loads in their rates[45]. With restructuring, the trend is to restrict loads to operation at near zero reactive power demand (a 1.0 power factor).

The system operators limits loads to power factors between 0.97 lagging (absorbing reactive power) and 0.99 leading. This would help to maintain power reliability of the system and avoid the problems of market power in which company could use its transmission and distribution lines to limit competition for distributed generation and increase its power prices.

DFIG and Reactive Power Management

Distributing generation resources throughout the power system have a beneficial effect if the generation has the ability to supply reactive power. Without this ability to control reactive-power output, performance of the transmission and distribution system can be degraded. DFIGs are an attractive choice for small, grid-connected generation for various reasons. Primarily, they are relatively inexpensive[46]. They do not require synchronizing and have mechanical characteristics that are appealing for application as wind based DGs. They also absorb reactive power rather than generate it, and are controllable. If the output from the DFIG fluctuates (as wind does), the reactive demand of the generator fluctuates as well, compounding voltage-control problems for the transmission system. DFIGs can be compensated with static capacitors, but this strategy does not address the fluctuation problem or provide controlled voltage support. Many distributed generation resources are now being coupled to the grid through solid-state power electronics to allow the prime mover's speed to vary independently of the power-system frequency[47,60]. For wind, this use of solid-state electronics can improve the energy capture.

In fact, most devices do not have to be providing active power for the full range of reactive control to be available. The generation prime mover, for example, the turbine, can be out of service while the reactive component is fully functional. This technological development (solid-state power electronics) has turned a potential problem into a benefit, allowing distributed resources to contribute to voltage control[52].Synchronous generators, SVC and various types of other DFIG equipment are used to maintain voltages throughout the transmission system. Injecting reactive power into the system raises voltages, and absorbing reactive power lowers voltages[48].

Voltage-support requirements are a function of the locations and magnitudes of DFIGs outputs and customer loads and of the configuration of the DFIG transmission and distribution system.These requirements can differ substantially from location to location and can change rapidly as the location and magnitude of DFIG generation and load change.

At very low levels of system load, transmission and distribution lines act as capacitors and increase voltages and at high levels of load, however, they absorb reactive power and thereby lower voltages. Most transmission-system equipment (for example, capacitors, inductors, and tap-changing transformers) is static but can be switched to respond to changes in voltage-support requirements [53, 54]. A more efficienct and reliable way is to control the DFIF reactive power using a reactive power participation factor that compares the generated/injected reactive power and the reactive power absorbed by the loads.

System operation has three objectives when managing reactive power and voltages[55].First, it must maintain adequate voltages throughout the transmission and distribution system for both current and contingency conditions.Second, it seeks to minimize congestion of real-power flows.Third, it seeks to minimize real-power losses.However, the mechanisms that system operators use to acquire and deploy reactive-power resources are changing .These mechanisms must be fair to all parties as well as effective.

B Participation factors

Participation factors are non dimensional scalars that measure the interaction between the modes and the state variables of a linear system .Participation factors were introduced by Verghese, P´erez-Arriaga and Schweppe [18],[19],[20] as a means for ranking the relative interactions between system modes and system states.The concept of the Selective Modal Analysis (SMA) approach introduced by these authors found its first applications in the field of electric power systems for load flow analysis, order reduction and controller design .

Other definitions of participation factors were introduced by Abed et al [21] so as to achieve a conceptual framework that doesn’t hinge on any particular choice of initial condition. The initial condition is modeled as an uncertain quantity, which can be viewed either in a set-valued or a probabilistic setting. If the initial condition uncertainty obeys a symmetry condition, the new definitions are found to reduce to the original definition of participation factors.

Application of Real power Participation Factors in Power Systems

In balanced transmission systems, distributed slack buses were introduced to remedy the inadequacy of a single slack bus.

Real power Participation factors have been applied to assign the system loss to multiple generators during power flow calculations. In previous works,these participation factors are constant values and can be determined by different methods. In [24, 25], the participation factors are related to the characteristics of turbines on each generator bus and load allocation. In [22], the authors applied participation factors using combined cost and reliability criteria in power flow for fair pricing. In [23], the author provides a method of choosing participation factors based on the scheduled generator outputs.

The participation factors in [26] are applied to minimize active power generation using the non linear version of the Interior Point Method(IPM).With increasing interest on reactive power dispatch and control in distribution systems,reactive power control for DGs also has become possible[27,28].The amount of reactive reserves at generating stations is a measure of the degree of voltage stability. With this perspective, an optimized reactive reserve management scheme based on the optimal power flow presented in [29] show that detailed models of generator limiters, such as those for armature and field current limiting must be considered in order to utilize the maximum reactive power capability of generators, so as to meet reactive power demands during voltage emergencies. Participation factors for each generator in the management scheme are predetermined based on the voltage-VAR (V-Q) curve methodology and the results prove that the proposed method can improve both static and dynamic voltage stability. Optimization Algorithms for reactive power have been presented in [34] by exact loss formula,in [33] by PSO and by GA in[32] .In[30,31], the management of reactive power generation to improve the voltage stability margin using modal analysis technique is done and the simulation results show that after the optimal reactive power re-scheduling, the active/reactive power losses are decreased. All these optimization methods provide no means of distributing the slack to various DGs in the power system. . The proposed constant participation factor index in [34,35] quantifies the reactive support need of different areas and generators to maintain adequate voltage stability margin

II. FORMULATION OF COMBINED PARTICIPATION FACTORS

S .Tong and K.Miu [35,36,37] ,applied the distributed slack bus participation factors to distribute real power loss to participating sources. In these cases,the participation factor, $K_{i,}$ for source i, is calculated as follows:

$$\mathrm{K}i = \frac{\mathrm{P}_{Gi}^{loss}}{\mathrm{P}_{loss}} \quad i = 0,1,2,\ldots n$$

$$where \sum_{i=0}^{n} \mathrm{K}_i = 1 \qquad \text{……….(1)}$$

$$\mathrm{P}_{Gi}^{loss} = \mathrm{P}_{Gi}^{lossa} + \mathrm{P}_{Gi}^{lossb} + \mathrm{P}_{Gi}^{loss,c}$$

Where ,0 the substation index, n the number of participating DGs in the system, P_{loss} the total real power loss in the system, P_{Gi}^{loss} the loss associated with generator *i*, $P_{Gi}^{loss,p}$ the loss associated with generator *i*, phase p

However, this method of real power participation factor do not provide a procedure for distributing the optimized reactive losses in the various DFIG buses at the same time maintaining the voltage stability.This paper will investigate the criteria of applying optimized reactive power loss distribution to a distributed slack bus model in power flow study by modeling the relation:

$$\mathrm{K}t = \frac{Q_{Gi}^{loss}}{Q_{loss}} \quad i = 0,1,2,\ldots n$$

$$where \sum_{i=0}^{n} \mathrm{K}t = 1 \qquad \text{…………(2)}$$

$$Q_{Gi}^{loss} = Q_{Gi}^{lossa} + Q_{Gi}^{lossb} + Q_{Gi}^{loss,c}$$

Where 0 is the substation index,n the number of participating DGs in the system, Q_{los} the total real power loss in the system, Q_{Gi}^{loss} the loss associated with generator *and* $Q_{Gi}^{loss,p}$ the loss associated with generator *i*, phase *p*

Equation (2) represents a function for he DFIG reactive power participation factor.This paper also investigates the differences between the participation factors of real power and reactive power contributions and how the two types of participation factors can be combined. That is, the feasibility of the relation:

Where K is the combined participation factor obtained as a vector sum of equations (1) and (2).s

$$K = K_i + j\mathrm{K}t = \frac{P_{Gi}^{loss}}{P_{loss}} + \frac{Q_{Gi}^{loss}}{Q_{loss}} \quad i = 1,2\ldots n \text{…………………………….(3)}$$

Penalty Factors

In this paper ,non negative participation factors are desired. However, rate of power loss with respect to DFIG input (sensitivities) can be negative,since penalty factors are defined as[38] ;

For real power,

$$L_{ip} = \frac{1}{1 - \dfrac{\partial P_L}{\partial P_{Gi}}} \text{……………(4)}$$

For reactive power,the reactive power penalty factors are defined in this paper as,

$$L_{iQ} = \frac{1}{1 - \dfrac{\partial Q_L}{\partial Q_{Gi}}} \text{………..(5)}$$

It is noted that in economic dispatch[40,41] with line loss considerations,the real power penalty factors were derived through the method of Lagrange multipliers. These penalty factors based on sensitivities are nonnegative, and reflect the impact of transmission system loss to real power injections from units, which are dispersed throughout the system. In this paper , these penalty factors are derived using for both real and reactive power and then used to obtain nonnegative combined participation factors.That is**,** the combined penalty factors are defined as ,

$$L = L_{iP+j} L_{iQ} \text{………..(6)}$$

Participation factor sensitivities

The network sensitivity combined participation factors incorporate the concept of network sensitivities and penalty factors to distribute the slack. These participation factors implicitly include effects of network parameters and load distribution through the sensitivities of system real power loss to real power injections and reactive power loss to reactive power injections reapectively.Since the sensitivities can be negative, penalty factors are applied to keep participation factors nonnegative.

The sensitivities, $\partial P_{loss} / \partial P_i$ where P_{loss} represents real power loss and P_i represents the real power injection to bus *i* , is addressed in [35,36,37]. They will be derived and computed at each power flow iteration as follows, For real power,

$$\begin{bmatrix} \dfrac{\partial P_{loss}}{\partial P} \\ \dfrac{\partial P_{loss}}{\partial Q} \end{bmatrix} = \left[J^{T}\right]^{-1} \begin{bmatrix} \dfrac{\partial P_{loss}}{\partial \theta} \\ \dfrac{\partial P_{loss}}{\partial |V|} \end{bmatrix} \ldots\ldots\ldots\ldots.(7)$$

$$\begin{bmatrix} \dfrac{\partial Q_{loss}}{\partial Q} \\ \dfrac{\partial Q_{loss}}{\partial P} \end{bmatrix} = \left[J^{T}\right]^{-1} \begin{bmatrix} \dfrac{\partial Q_{loss}}{\partial \theta} \\ \dfrac{\partial Q_{loss}}{\partial |V|} \end{bmatrix} \ldots\ldots\ldots\ldots(8)$$

For reactive power,the sensitivities for DFIG reactive power are defined as ,

Where:J : Jacobian matrix for three-phase power flow with a single slack bus .Since R, X values of network components, voltage phase angles θ and voltage magnitudes V are included in J , the system network parameters, and load distribution are implicitly included in the sensitivities and hence in the combined participation factors.

A Distributed Slack Bus Models

Participation factors for distribution systems should reflect network parameters, load distribution, generator locations and capacities. Two methods used to calculate such network based participation factors are the network sensitivity participation factors and generator domain participation factors

The generator domain participation factors were studied extensively by [43], therefore this paper will address the network sensitivity participation factors then apply both methods in slack bus placement in the distribution system with DFIGs. The network sensitivity participation factors incorporate the concept of network sensitivities and penalty factors to distribute the slack(real and reactive power losses).These participation factors implicitly include effects of network parameters and load distribution through the sensitivities of system real and reactive power losses and real and reactive power injections. In addition, since balanced and unbalanced systems can be considered in actual load flow analysis, phase sensitivities on the same bus could be different.

Therefore, the average phase sensitivity or maximum phase sensitivity can be utilized.

Also, for a single slack bus model, the system loss is independent of the real and reactive power injections of the reference bus, whose penalty factor is set as one.

Thus, the penalty factors are defined as:

Based on average phase sensitivity

$$L_{o} = 1$$

$$L_{i} = \frac{1}{1 - \frac{1}{3}\left(\frac{\partial P_{loss}}{\partial P_{Gi}^{a}} + \frac{\partial P_{loss}}{\partial P_{Gi}^{b}} + \frac{\partial P_{loss}}{\partial P_{Gi}^{c}}\right)} \ldots\ldots\ldots.(9a).$$

$$Lt = \frac{1}{1 - \frac{1}{3}\left(\frac{\partial Q_{loss}}{\partial Q_{Gi}^{a}} + \frac{\partial Q_{loss}}{\partial Q_{Gi}^{b}} + \frac{\partial Q_{loss}}{\partial Q_{Gi}^{c}}\right)} \ldots\ldots\ldots.(9b)$$

Based on maximum phase sensitivity

$$L_{o} = 1$$

$$L_{i} = \frac{1}{1 - Max\left(\frac{\partial P_{loss}}{\partial P_{Gi}^{a}}, \frac{\partial P_{loss}}{\partial P_{Gi}^{b}}, \frac{\partial P_{loss}}{\partial P_{Gi}^{c}}\right)} \ldots\ldots\ldots.(10a)$$

$$Lt = \frac{1}{1 - Max\left(\frac{\partial Q_{loss}}{\partial Q_{Gi}^{a}}, \frac{\partial Q_{loss}}{\partial Q_{Gi}^{b}}, \frac{\partial Q_{loss}}{\partial Q_{Gi}^{c}}\right)} \ldots\ldots\ldots(10b)$$

In the above equations ,all penalty factors are nonnegative. At first glance, the sensitivity values are not necessarily nonnegative; however, when calculating in per unit with realistic power distribution components, the sensitivity values are less than one, which results in nonnegative L_i and $L_{t.}$

These penalty factors also capture DFIGs' effects to system losses through sensitivities.When a participating source is installed far from load centers, more loss occurs on the path to serve the same amount of load from this source; then, its sensitivity should be larger than the sources, who are installed closer to load centers. In other words, a larger sensitivity value results in a larger penalty factor.

In addition, since sensitivities or these penalty factors only represent the ratios of system real power loss changes, the associated real power load served by each participating source, P_{Gi}^{load}, should also need to be included in its participation factor to scale its associated real power loss. Therefore, network sensitivity real power participation factors with applied penalty factors are determined as[35,36,37]:

$$K_i = \frac{L_i P_{Gi}^{load}}{\sum_{j=0}^{m} L_i P_{Gi}^{load}} \text{.........}(11)$$

Where, P_{Gi}^{load} : real power load associated with generator *i*

Since *J* changes at each iteration, L_i and the participation factors are iterative. The real power load associated with generator *i* , P_{Gi}^{load} , is a set value before power flow calculations, which can be considered as generator *i* 's scheduled output to serve a desired amount of load.

A corresponding reactive power participation factors can also be defined similarly.Hence,the combined participation factor IN equation (3) becomes

$$K = \frac{L_i P_{Gi}^{load}}{\sum_{j=0}^{m} L_i \; P_{Gi}^{load}} + \frac{L_t Q_{Gi}^{load}}{\sum_{j=o}^{n} L_t \; Q_{Gi}^{load}} \text{...........}(12)$$

Where K is the combined participation factor and the loss sensitivities are derived using the method of Lagrange multipliers.

B Solution Algorithm Reactive Power Participation Factors

A Newton Raphson Solver Incorporating the distributed slack model with iterative participation factors is used .The algorithm was proposed in [36] for real power participation factors and in this paper it is applied for the reactive power participation factors.This algorithm works for both network sensitivity and generator domain participation factors.The steps for the algorithm are as follows:

Step 1 Choose an initial guess at $x^{(0)}$

Step 2 Set the iteration counter at $k = 0$

Step 3 Set desired Q_{Gi}^{load} *and initial* K_t

Step 4 Evaluate $F^{(K)}(X^{(K)})$

Step 5 Stop if $\left|F^{(K)}\right| \leq Tolerance$

Step 6 Evaluate $J_e^{(k)} = \frac{\partial F}{\partial x}$

Step 7 Solve $J_e^{(k)} \Delta x^{(k)} = -F^{(k)}$

Step 8 Let $x^{(k+1)} = x^{(k)} + \Delta x^{(k)}$

Step 9 Let $k = k + 1$

Step 10 Check real and reactive power limits of the participating DFIGs.If the calculated real/reactive power output of a DFIG violated its limits,this DFIGs can not be considered as a participating source which accounts for slack and is modeled as a constant PQ injection Then go to **Step 3**

Step 11 Upgrade calculation information.For sensitivity participation factors,calculate sensitivities and for generator domain participation factors,find positive power flow directions and distinguish generator domains for the substation and participating DFIGs.

Step 12 Calculate reactive power participation factors $K_t^{(k)}$ *and* $K_0^{(K)}$,and go to **Step 4.**

For real power participation factors ,the same algorithm is used but with **Step 3** with the desired P_{Gi}^{load} *and initial* K_i

C 33 Bus Radial Distribution Test System

IEEE recommended balanced distribution systems include the radial 16 Bus,30 Bus ,33 Bus 94 Bus 69 Bus and 119 Bus systems[42],with the 33 Bus and the 69 Bus being commonly for most simulations used because they are balanced topologies.

In this paper, the distribution test systems used is the radial 33 bus systems. The system has 32 sectionalizing branches, 5 tie switches , nominal voltage of 12.66KV and a total system load 3.72 MW and 2.3 MVAR. The original total real power loss and reactive power loss in the system are 221.4346 Kw (5.95%) and 150.1784 kVAR (6.53%). The network diagram is as shown in figure 1

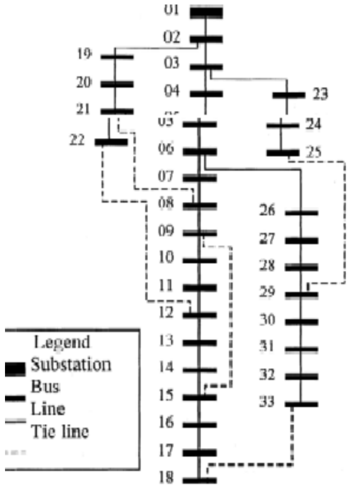

Figure 2:IEEE 33 Bus Radial Distribution System

TABLE I
IEEE 33 BUS RADIAL SYSTEM LOAD DATA

Bus No.	P_L (kW)	Q_L (kVAr)	Bus No.	P_L (kW)	Q_L (kVAr)
2	100	60	18	90	40
3	90	40	19	90	40
4	120	80	20	90	40
5	60	30	21	90	40
6	60	20	22	90	40
7	200	100	23	90	50
8	200	100	24	420	200
9	60	20	25	420	200
10	60	20	26	60	25
11	45	30	27	60	25
12	60	35	28	60	20
13	60	35	29	120	70
14	120	80	30	200	100
15	60	10	31	150	70
16	60	20	32	210	100
17	60	20	33	60	40

TABLE II
IEEE 33 BUS RADIAL SYSTEM BUS DATA

Branch Number	Sending end bus	Receiving end bus	R (Ω)	X (Ω)
10	10	11	0.1967	0.0651
11	11	12	0.3744	0.1298
12	12	13	1.4680	1.1549
13	13	14	0.5416	0.7129
14	14	15	0.5909	0.5260
15	15	16	0.7462	0.5449
16	16	17	1.2889	1.7210
17	17	18	0.7320	0.5739
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3555
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3084
23	23	24	0.8980	0.7091
24	24	25	0.8959	0.7071
25	6	26	0.2031	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0589	0.9338
28	28	29	0.8043	0.7006
29	29	30	0.5074	0.2585
30	30	31	0.9745	0.9629
31	31	32	0.3105	0.3619
32	32	33	0.3411	0.5302
34	8	21	2.0000	2.0000
36	9	15	2.0000	2.0000
35	12	22	2.0000	2.0000
37	18	33	0.5000	0.5000
33	25	29	0.5000	0.5000

The transformer between Bus 6 and Bus 26 services 1.3681 MW and 0.3098 Mvar dispersed loads in a commercial and residential area.

With no DFIG installed 10.51 kW (1.53% of total system real power loss) occurs in the high density load area and 204.59 kW (92.39% of the total loss) occurred in the commercial and residential area from its higher network resistances and branch currents.

Two cases will be investigated. In each case, simulation results from three-phase power flow analysis using different slack bus models will be compared. They are as follows;Case 1: the DFIG is installed on Bus 18 and Case 2: the DFIG is installed on Bus 19.

In both cases, one DFIG is assumed to service 1,500kW, 750KVAR loads, that is approximately 40% DFIG penetration. The DFIG installed on Bus 18 is expected to have a larger impact on system real and reactive power losses and a larger percentage of system loss contribution. Thus, it should be assigned a larger participation factor than the DFIG installed on Bus 19 to serve the same amount of real and reactive power loads.

D Simulation Results For The 33 Bus Radial System

Simulation results including the real and reactive power participation factors, real and reactive power outputs obtained using the different slack bus models of the 33 bus radial distribution system are as shown in the Table3 and Table 4 below for cases 1 and case 2 respectively.

Observations

From these numerical simulation results, the impacts of different slack bus models for distributed generation with DFIGs were observed. For the single slack bus model, both cases keep the DFIGs at the same output out 1.5MW and 750KVAR.

The distributed slack bus model with non-iterative participation factors based on scheduled DFIG outputs alone has the same real power participation factors values in both cases. however he corresponding combined participation factors are different,with the combined factors being higher in case A than case B.Thus, with the same DFIG output, the amount of the KVAR output attributed to loads compared to the system losses are the same even though the DFIG is located at different locations. Since this method does not capture the effects of DFIG locations on system studies, it is not recommended.

The distributed slack bus model with sensitivity participation factors were computed in two ways: based on average sensitivities and maximum phase sensitivities. The resulting COMINED participation factors were different between these two methods. It is noted that both methods assigned larger participation factors to the DFIG on Bus 18 than when the DFIG was placed on Bus 19. Thus the sensitivity and penalty factor approach performed, as expected, with respect to attributing higher losses to the DFIG at bus 18.

However, the combined participation factors between the DFIG at bus 19 compared to the one at bus 18 was small. Thus, concerns arise as to whether sensitivity measures are significant enough to fully capture the effects of DFIG locations.

Key:

A-Single slack Bus Model,
B-Distributed Slack bus model based on DFIG capacity,
C-Distributed Slack bus model based on average sensitivity,
D-Distributed Slack bus model based on maximum sensitivity,
E-Distributed Slack bus model based on DFIG domain.

TABLE III
Case A :33 Bus Radial Distribution System with one DFIG on Bus 18 to service 1500 KW ,750 KVAR load

	A	B.	C	D	E
Sub.Par.k_0	1	0.7515	0.7468	0.7497	0.6749
DFIG par.$k_{i=19}$	0	0.2485	0.2532	0.2503	0.3251
DFIG par.$k_{t=19}$	0	0.2356	0.2448	0.2709	0.3099
Com par .K	1	0.3424	0.3552	0.3688	0.4492
Ø(deg)	0	43.47	44.03	47.26	43.63
$P_{sub}^{out}(MW)$	475.052	470.554	470.554	471.554	468.593
$P_{DFIG}^{out}(MW)$	1.5000	1.5232	1.5232	1.5232	1.5629
$Q_{DFIGG}^{out}(KVAR)$	750.0000	750.0083	750.0128	750.0156	750.0165
$P_{loss}^{sys}(MW)$	221.4340	221.4238	221.4238	221.4238	220.4225
$Q_{loss}^{sys}(KVAR)$	150.1790	149.1788	149.1775	149.1765	149.1755

TABLE IV
Case B:33 Bus Radial Distribution System with one DFIG on Bus 19 to service 1500 KW ,750 KVAR load

	A	B.	C	D	E
Sub.Par.k_0	1	0.7515	0.7633	0.7555	0.9866
DFIG.par.$k_{i=19}$	0	0.2485	0.2367	0.2445	0.0134
DFIG.par.$k_{t=19}$	0	0.2296	0.2295	0.2386	0.0108
Com.par .K	1	0.3384	0.3297	0.3416	0.0172
Ø(deg)	0	42.74	44.12	44.30	38.87
$P_{sub}^{out}(MW)$	476.3162	471.6651	471.6651	471.6651	476.2040
$P_{DFIG}^{out}(MW)$	1.5000	1.5565	1.5565	1.5565	1.5012
$Q_{DFIGG}^{out}(KVAR)$	750.0000	750.0083	750.0128	750.0156	750.0165
$P_{loss}^{sys}(MW)$	221.4346	221.4344	221.4340	221.4341	220.9992
$Q_{loss}^{sys}(KVAR)$	150.1784	149.1780	149.1776	149.1770	149.1765

The distributed slack bus model with DFIG domain participation factors has a much larger real and reactive participation factors for the DFIG on Bus 18 than the DFIG on Bus 19.

This clearly shows that relating the real and reactive participation factors with DFIG locations, network parameters and load distribution yield more distinct distributed slack bus combined participation factors. Therefore, real ,reactive and combined participation factors determined by DFIG domains are recommended for the distributed slack bus model.

III. CONCLUSIONS

This paper has provided a background work toward the modification of the traditional load flow study. Slack bus modeling for distribution power flow analysis has been studied and investigated. First,the distribution power flow with a distributed slack bus model for DFIGs has been studied.Second ,scalar participation factors to distribute uncertain real and reactive power system losses for three phase power flow calculations have been formulated.Also two methods to calculate network-based participation factors have been presented ;sensitivity-based method and generator domain based method.Lastly a GA based Newton-Raphson solver implemented the distributed slack model with iterative combined participation factors.

The distribution power flow with a single slack bus model was revisited, and a slack bus model was developed for distribution systems with DFIGs. The combined participation factors based on generator domains, which are explicitly relative to network parameters and load distributions, demonstrate their ability to capture network characteristics and to scale loss contributions of sources surpasses other participation factors. Therefore, the distributed slack model with generator domain participation factors is recommended for the allocation of real and reactive power losses to various buses.The combined participation factors are higher than he real power participation factors formultated by [35,36,37]and they provide a better way of obtaining a distributed slack bus model for a DFIG based distribution system.

The distribution power flow with a distributed slack bus model presented in this paper can be applied in many areas. These include DFIF and capacitor placement and sizing network reconfiguration, Distribution system expansion , service restoration and reactive power control These applications can also be investigated.

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