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Particle Swarm Optimized Power Grid Frequency Stability Control Scheme in the Presence of Wind Energy Sources.

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Abstract - **Renewable energy sources (RES) have become a subject of interest world-wide, including in Kenya where recently a 310 MW Wind Power plant was commissioned. They are clean energy technologies and relatively cheaper compared to fossil-fuels. They do not inherently provide system inertia from rotating masses of the rotor of the wind turbine hence when integrated into the grid pose electrical power system frequency instability. The optimization and load flow were conducted using particle swarm optimization algorithm and Newton Raphson algorithm. Results showed that the voltage profile and frequency response profile improved significantly as the percentage of wind penetration increased in the grid. For the test system considered, the maximum wind penetration was 32.1%. Notably, as the percentage of wind penetration increased, the rate of change of frequency worsened because of the intermittent nature of wind energy source.**

Index Terms: **Frequency instability, system inertia, particle swarm optimization.**

I. INTRODUCTION

Renewable energy sources are clean energy technologies and in some cases occur in abundance and mitigate against sustained depletion of fossil-fuels and support energy diversification [1].These sources reduce carbon dioxide emissions and hence the effects of global warming [2]. Some of the common challenges are the rare species of birds have become victims of the windmills and wind turbines world-wide. The beauty of the land is destroyed in using some of the wind turbines to generate electrical power and cost of land drops as result of their establishment.

Wind energy conversion systems are known to offer less or no support at all to system frequency stability due to lack of system inertia because of the presence power electronic converters employed for constant power output during generation [1]- [2]. For example, islanded grids suffer severe frequency instabilities in the presence of these technologies because of lack of support from conventional sources of energy [1]- [3]. Research has proposed use of natural or synthetic methods to provide system inertia. This includes use of renewable energy storage systems (RESS) [4], [5].This is a noble idea but increases investment cost because it supports setting up more like parallel plants to stabilise grid system frequency in the event of transient disturbances.

Natural methods of providing system inertia avoid establishment of parallel plants but have dire consequences related to operation, control and support of frequency stability. The power system frequency control has three stages [6], [7], [8]- [9].

This paper is organised as follows: Section II delves into particle swarm optimization in the presence of wind energy sources, problem formulation of power extraction from wind turbine is covered in Section III. Section IV provides the IEEE 39 Bus test system model in MATLAB environment and coded using particle swarm optimization (PSO) algorithm approach. Result analysis and discussions are done in section V and finally conclusion is given in section VI.

II. PARTICLE SWARM OPTIMIZATION (PSO) IN THE PRESENCE OF WIND ENERGY SOURCES

This paper is not the first one to use PSO in optimization of either energy or power from the Variable Speed Wind Turbines (VSWT). Pareto-Dominance was used with Multi-objective PSO to select emulated inertial response control parameters on a micro grid [10].Parameters of the inertial controller and those that satisfy multiple and conflicting power system objectives were selected for the test system. In conclusion, design preference influences parameter selection for example weaker grid require aggressive inertial response because frequency stability is a major concern. In post disturbance support, inertial response demand is limited hence parameter settings will change. Pitch angle and rotor speed optimization in VSWT were also tested using differential evolution [11]. The effect of wind power penetration on frequency stability and frequency regulation capability were examined [12]. The results showed that the integration of wind power leads to reduced frequency stability because of reduced overall system inertia.

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III. PROBLEM FORMULATION

From the swing equation, the accelerating torque T_a is given by [6], [13].

$$J\dot{W} = T_a \quad (1)$$

Where:

$\dot{W}$ is average angular acceleration in radians/second squared (rad/s^2), J is rotor moment of inertia in Kg-m^2, T_a is accelerating torque in N.m.

$$T_m - T_e = T_a \quad (2)$$

T_m is the driving mechanical torque and T_e is the retarding electrical torque.

Similarly,

For a synchronous machine as derived from [14],

$$\frac{df}{dt} = \frac{\Delta P * f_0}{2 * GH} \quad (3)$$

ΔP is the change in power, f_0 refers to the nominal frequency in Hz, $\frac{df}{dt}$ is the rate of change of frequency (ROCOF), G is rated apparent power, H is inertia time constant. Therefore, to determine, the frequency deviations Δf, it is given by,

$$\Delta f = f_0 - f_{nadir} \quad (4)$$

$$\Delta f = f_0 - [(2GH * \frac{df}{dt})/\Delta P] \quad (5)$$

f_{nadir} is the minimum frequency value in Hz.To extract maximum kinetic energy, we should maximize the deceleration of the rotor. Hence, min $\frac{df}{dt}$ and min Δf.

The equations for extraction of wind power from the wind turbine are derived from [6], [15].

Considering primary power reserve margin, and loading the turbine at 85%, then

$$P_{opt} \geq 0.85 P_{opt} + \Delta Pke \quad (6)$$

$$\Delta Pke \leq 0.15 P_{opt} \quad (7)$$

ΔPke is change in power due to kinetic energy, P_{opt} is optimal power of the generator in MW

Ignoring windage, iron and frictional losses,

$$P_G = P_t \quad (8)$$

P_G is total generated electrical power in MW, Pt is total turbine power equal to total mechanical power

According to [16], the accelerating power is given by

$$JW_r\dot{W}_r = P_{in} - (P_{ref} + \Delta Pke) \quad (9)$$

W_r is mechanical rotational speed, P_{ref} is reference power and P_{in} is mechanical input power of the wind turbine.

The power imbalance will be catered by the difference between the input power and power extraction from de-loaded mode due to deceleration of the rotor speed to counter frequency drop. Ignoring variable and fixed losses in the Variable Speed Wind Turbine

$$\Delta Pke = P_{in} - \sum_{k=1}^{n} (JW_{del} \frac{W_{del}}{dt}) \quad (10)$$

W_{del} is the de-loaded rotor speed in radians per second (rad/s).Taking into consideration a wind farm with n wind turbines with reference to equation (10), then maximize the extraction of accelerating power from the wind turbine. Since the reference power is a constant, P_{ref}, then considering a maximum power point tracking (MPPT) curve has maximum and minimum rotor speeds in de-loaded mode.

$$Max\ \Delta Pke = Max\ \{\sum_{k=1}^{n} (P_{in} - JW_{del} \frac{W_{del}}{dt})\} \quad (11)$$

The wind farm power output, according to [16] is given by,

$$P_{ref,wf} = \sum_{k=1}^{n} P_{del,k} = \sum_{k=1}^{n} 0.85 P_{opt,k} \quad (12)$$

$P_{ref,wf}$ is the system operator's output command, $P_{del,k}$ is the de-loaded power reference. The objective function is

$$Max\ \Delta Pke = Max \left\{\sum_{k=1}^{n} \left(P_{in,k} - JW_{del,k} \frac{\dot{W}_{del,k}}{dt}\right)\right\} \quad (13)$$

Subject to the constraints:

$$\text{Total } \Delta Pke \leq 0.15 \text{ Total } P_{opt} \quad (14)$$

$$P_{min} \leq P_{del} \leq P_{max} \quad (15)$$

$$W_{del,min} \leq W_{del} \leq W_{max} \quad (16)$$

$$\beta min \leq 0 \leq \beta\ max \quad (17)$$

$$C_p \leq 0.59 \quad (18)$$

β is the pitch angle in degrees, C_p is the power coefficient.

IV. PARTICLE SWARM (PSO) APPROACH

In this case, the objective function was coded using PSO and the output power was the best global power and optimal rotor speed. The derived power was used as an input in the load flow using Newton Raphson algorithm for IEEE 39 Bus test system to display the voltage profile and frequency response when a

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disturbance was introduced in the grid. The mapping of the problem to particle swarm optimization (PSO) is shown in Table I. The power coefficient is derived from wind velocity (m/s) inputs of 4,7,8,9,10,11,12,14 with judiciously selected tip speed ratio range of 1-8,and beta (β) values of 0,0.5,1,2,3,4,5 and 6 degrees and wind turbine blade radius of 35.25 metres.

There were five scenarios in total. Scenario I: Without wind energy sources in the grid. Scenario II: With one wind energy source in the grid. Scenario III: With two wind energy sources in the grid. Scenario IV: With two wind energy sources and Bus 39 generator tripped. Scenario V: With two wind energy sources and Buses 38 and 39 tripped. In the first 3 instances, rotor angle disturbance was introduced after displacement of the conventional generators by wind generators. In the fourth and fifth instances, generators at buses 39 and 38-39 buses were tripped respectively.

TABLE I. MAPPING OF THE PROBLEM TO PARTICLE SWARM OPTIMIZATION ALGORITHM.

No	Parameter description	Algorithm Representation
1	Rotor speed in radians per second	Particle
2	Group of wind Turbines' inertial response	Swarm
3	Optimal Power due to kinetic energy released	Destination
4	Feasible region or region of the desirable Power injected.	Center of the swarm
5	Fitness function	Objective Function

V. RESULTS AND DISCUSSIONS

A. Scenario I: Without Wind Farm Integrated in the Grid

The grid system frequency achieved was 49.9963 Hz and without PSO optimization. The rate of change of frequency (ROCOF) was 0.030389 Hz/s and system inertia of 36 seconds and the voltage profile was 1±0.1 per unit within the limits and the grid was stable.

B. Scenario II: With One Wind Farm Integrated in the Grid

In this case the grid system frequency achieved was 49.9966 Hz with PSO optimization. The ROCOF was 0.029972 Hz/s with system inertia of 36.5 seconds and voltage profile of 1±0.1 per unit. The hydro generator at Bus 39 rated at 1000 MW was displaced by one wind farm consisting of 400 wind turbines and none of the units was tripped in the IEEE 39 Bus test system. The wind farm produced 1083.32 MW based on a Doubly Fed Induction Generator (DFIG) model in optimal mode at 0.4535 power coefficient. The de-loaded mode power coefficient was set at 0.3617 with tip speed ratio of 7 at one degree pitch angle and power generated was 917.24 MW. On disturbance introduction, the power coefficient was set at 0.4535 with a value of 8 for tip ratio speed and zero degree pitch angle. The grid was relatively stable compared to scenario I.

C. Scenario III: With Two Wind Farms Integrated in the Grid

Two wind farms each with 200 wind turbines were placed at Buses 34 and 39 randomly. This displaced steam and hydro turbines with initial power generations of 508 MW and 1000 MW respectively. The two wind farms initially operated in de-loaded mode with a power coefficient of 0.3617 at one degree pitch angle and a value of 7 tip speed ratio that produced power of 463.87 MW each. In the optimal mode, at 8 tip speed ratio and zero degree pitch angle with power coefficient of 0.4535 power produced was 539.07 MW. In de-loaded mode, total power generated in the grid was 5521.23 MW. Power generated from wind was 927.74 MW which accounted for 16.80 % of the total power generated. The system frequency dropped to 49.9965 Hz with a ROCOF of 0.032656 Hz/s. The voltage profile was within the limits of 1±0.1 per unit. The system inertia dropped to 33.5 seconds. Hence the grid became relatively unstable though with minimal impact on the grid.

D. Scenario IV: With Two Wind Farms Integrated in the Grid and Bus 39 Generator Tripped

Buses 34 and 35 generators were replaced with two wind farms with 200 wind turbines at each bus. They displaced both steam and gas turbines of 508 MW and 650 MW capacities respectively. In de-loaded mode, a power coefficient of 0.3617 produced 619.4 MW at each bus. The percentage of wind penetration was 20.04 % because the total generation increased to 6182.28 MW from 6101.48 MW. In optimal mode, Bus 39 generator was tripped and settings of the wind turbine set to zero degree pitch angle and a value of 8 for tip speed ratio with a power coefficient of 0.4535 producing 740.88 MW of power. The system frequency was 49.9971 Hz with a ROCOF of 0.036466Hz/s. The system inertia was 30 seconds. The voltage profile remained within the limits of 1±0.1 per unit. Reduction in system inertia and a worse value of ROCOF compared to scenario III indicates the electrical power system is unstable.

E. Scenario V: With Two Wind Farms Integrated in the Grid and Buses 38 and 39 Generators Tripped

Buses 34 and 35 generators were replaced with wind two wind farms as in scenario IV, but generators 38 and 39 were both tripped. In the de-loaded mode, the PSO algorithm failed to run and give any results. In the optimal mode, with a power coefficient of 0.4535 for zero degree pitch angle and tip speed ratio of 8, power produced was 756.45 MW.The system inertia was 27 seconds. The voltage profile limits were violated recording values below 0.9 per unit. The system frequency

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dropped to 49.9968 Hz with a ROCOF of 0.040518 Hz/s. The grid was unstable with maximum wind penetration of 32.08%.

Generally, scenarios I-III recorded positive frequency improvement and voltage profile was relatively stable when rotor angle disturbance was introduced as shown in appendix A, Table II. The voltage and frequency responses for scenarios II and V are also displayed in appendix A: Fig. 1 and Fig. 2.

The results obtained from this study are more superior when frequencies from [10] are compared. The post support minimum frequency value was 49.37 Hz while this study obtained 49.9971 Hz. However, the systems are different because this study focussed on the grid while the former [10] on micro grid which is weaker compared to grid stability.

A. CONCLUSION.

The PSO improved frequency response in de-loaded mode from 49.9963Hz to 49.9971 Hz in case 4 but case 5 failed to execute.The ROCOF deteriorated from 0.030389 Hz/sec to 0.040518 Hz/sec.

This paper established that wind energy penetration percentage was limited to 32.08% beyond which frequency instability occurs. It also found out that displacement of conventional sources of power should consider the system inertia of specific generator being replaced. Some replacements could reduce the inertia by a large value and destabilise the grid.

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APPENDIX A

TABLE II. RESULTS OF THE PSO APPROACH.

SCENARIO	WIND FARMS (No.)	FREQUENCY (Hz)	ROCOF (Hz/s)	V (pu)	INERTIA(s)	DISPLACED GENERATOR BUS No.	GEN-TRIPPED BUS No.	SETTLING TIME (s)	STATUS OF THE GRID
I	0	49.9963	0.030389	1±0.1	36	None	None	0.91673	Stable
II	1	49.9966	0.029972	1±0.1	36.5	39	None	0.92946	Relatively stable compared to scenario I
III	2	49.9965	0.032656	1±0.1	33.5	39,34	None	0.85307	Relatively Unstable
IV	2	49.9971	0.036466	1±0.1	30	34,35	39	0.76394	Unstable
V	2	49.9968	0.040518	violated	27	34,35	38,39	0.68755	In optimal mode unstable/De-loaded mode does not operate

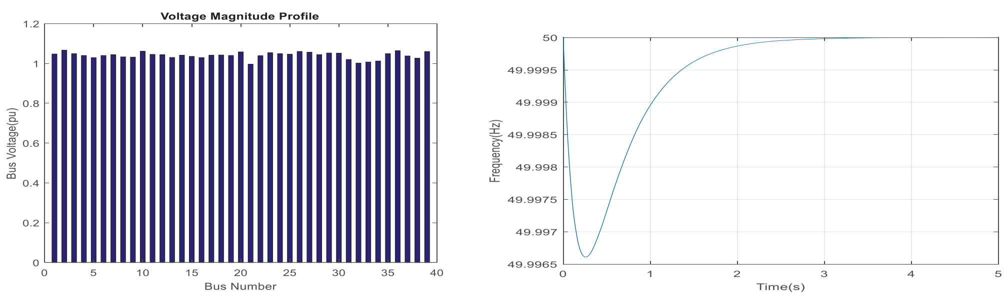

Fig. 1. Voltage Profile and Frequency Response of one Wind Farm integrated in the Grid

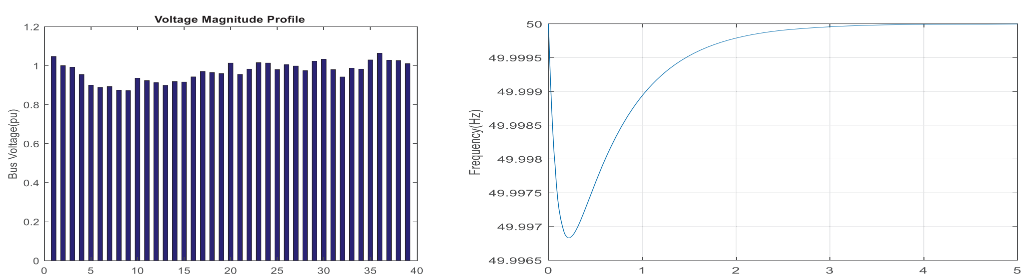

Fig. 2. Voltage Profile and Frequency Response of two Wind Farms integrated in the Grid with two Generators at Buses 38 and 39 tripped.

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