Effects of Renewable Energy on Frequency Stability: A Proposed Case Study of the Kenyan Grid

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Abstract: Renewable Energy (RE) units especially grid connected Wind and Solar PV which have no rotational inertia are effectively displacing the conventional generators and their rotating systems. This reduces both the cost of generation and environmental effects. However, this has implications on the frequency stability in that frequency dynamics become faster with low inertia. This makes frequency control complex and difficult and thus frequency stability becomes challenging. The frequency deviation should be kept small as Damaging Vibrations (DV) and Under Frequency Load Shedding (UFLS) occur for large deviations in the worst case, leading to total black out. For example, in Kenya, there has been increased penetration of RE especially wind and solar into the grid. On Tuesday 7th June 2016 at 1130Hrs, a nationwide black out hit the country for almost three hours when a monkey tripped at transformer at Gitaru Hydroelectric Power Station, leading to a loss of more than 180MW from the grid. This paper revisits Frequency Stability, UFLS and proposes a Combined Frequency with Renewable Energy Storage Cost (CFS) approach for mitigating frequency instability with RE. A brief outline of the Kenyan Case is also provided.

Key Words: Combined Frequency with Renewable Energy Storage Cost (CFS), Kenya, Damaging Vibrations (DV), Frequency Stability, Under Frequency Load Shedding (UFLS), Renewable Energy (RE)

I: INTRODUCTION

Power system stability is the continuance of intact operation of the power system following a disturbance. Power system security, on the other hand, is the degree of risk in the ability to survive imminent disturbances (contingencies) without interruption of load supply. Stability and security are time-varying attributes [1]. RE penetration reduces cost and environmental effects but due to their intermittent nature, this makes the power system insecure and thus unstable. Thus, with increased integration of RE to the grid, power system security is associated with the response of the system to whatever perturbations it is subject to plus the unpredictable nature of the RE Sources (RES)[2]. Normally, security evaluation requires the analysis of frequency voltage and rotor angle stability in the power system. In this paper, frequency stability with increased RE penetration is of concern.

II: FREQUENCY STABILITY WITH RENEWABLE ENERGY

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in significant imbalance between generation and load [1]. Large-scale deployment of RES has led to significant generation shares of variable RES in power systems worldwide. RES units, notably inverter-connected wind turbines and photovoltaic (PV) which do not provide sufficient rotational inertia, are effectively displacing conventional generators and their rotating machinery due to their reduced cost and environmental concerns[3]. The traditional assumption that grid inertia is sufficiently high with only small variations over time is thus not valid for power systems with high RES penetration[4]. This has implications for frequency dynamics and power system stability and operation. Frequency dynamics are faster in power systems with low rotational inertia, making frequency control and power system operation more challenging [5].This is the case with the integration of the intermittent RE into the grid. Next, we consider the Frequency Dynamics.

A: Frequency Dynamics with RE

The rotational energy (E) for a machine is defined by

$$E = \frac{1}{2} J\omega^2 \qquad (1)$$

where J is the moment of inertia of the synchronous machine and $\omega = 2\pi f$ is the rotating frequency of the machine.

The inertia constant, H, is given by

$$H = \frac{E}{S_B} = {}^{1}\!/_{2} \frac{J\omega^2}{S_B} \qquad (2)$$

where S_B is the rated power of the generator. H denotes the time duration during which the machine can supply its rated power solely with its stored kinetic energy E and this ranges between 2-10s. Some values of inertia H are as shown in the Table 1.0. from which, it is clear that RE systems have less interia hence their adverse effects on power system stability.

TABLE 1.0: INERTIA CONSTANTS

System Turbine	**H(s)**
Steam	4-9
Gas	3-4
Hydro	2-4
Wind	**2-5**
Solar PV	**0**

The power system frequency (f_0) at any instant is given by the relation

$$f_0 = \frac{2H * {}^{df}\!/_{dt}}{\Delta P_f} \qquad (3)$$

where ${}^{df}/_{dt}$ is the average rate of change of frequency (ROCOF) and $\Delta P = P_m - P_e$ is the power imbalance . P_m denotes the mechanical power supplied by the generator and P_e is the electric power demand.

Taking n to represent the normal and a abnormal operating conditions (after disturbance or fault), then

$$f_n = \frac{2H_n * {}^{df_n}/_{dt}}{\Delta P_{fn}} \qquad (4)$$

And

$$f_a = \frac{2H_a * {}^{df_a}/_{dt}}{\Delta P_{fa}} \qquad (5)$$

The frequency deviation (Δf) after disturbance or fault is thus given by

$$\Delta f = f_n - f_a = 2\left\{\left(\frac{H_n * {}^{df_n}/_{dt}}{P_{Gn} - P_{Dn}}\right) - \left(\frac{H_a * {}^{df_a}/_{dt}}{P_{Ga} - P_{Da}}\right)\right\} \qquad (6)$$

This equation is the one modeled as an optimization problem for minimization, that is,

$$\min \Delta f \ = \min 2\left\{ (\frac{H_n * {}^{df_n}/_{dt}}{P_{Gn} - P_{Dn}}) - (\frac{H_a * {}^{df_a}/_{dt}}{P_{Ga} - P_{Da}}) \right\} \qquad (7)$$

Frequency deviation is minimized subject to loads in each bus that sum up to total amount of load during a disturbance, P_{Da}. At the time of load shedding, all the variables are known except for the summation of loads in each bus which give rise to P_{Da}.

Traditionally, electricity generation is fully dispatchable, that is, it is controllable and involves rotating synchronous generators. Through their stored kinetic energy (E), they add rotational inertia which is a property of frequency dynamics and stability. Rotational inertia, H, minimizes Δf in case of frequency deviations rendering frequency dynamics slower thereby increasing available response time to react to fault events, for example, line losses, power plant outages or large scale set point changes of either generation or load unit.

Low levels of rotational inertia in a power system caused by inverter connected RES which do provide zero or little inertia have implications on frequency dynamics in that they are faster in power systems with low rotational inertia. This leads to a situation where traditional frequency control schemes become too slow for preventing large frequency deviations and their impeding consequences. Loss of rotational inertia and time variance of inertia can lead to new a frequency instability phenomena.

Due to the unpredictable nature of RE, there may be a mismatch between the generation of power and the demand of power. This causes deviations in the system frequency. In the case of a power deficit, the generation is less than the power demand leading to a reduction of speed and hence the system frequency goes down. On the other hand, if the generation of power is more than the demand, it will cause an increase in speed and hence an increase in the system frequency, thus leading to frequency instability. Frequency instability due to wind and PV is explained next.

In wind energy power generation, when fixed speed induction generators are used, it contributes to the inertia of a power system because the stator is directly connected to the grid and thus changes in frequency manifests as a change in speed. These speeds are resisted by the rotating mass leading to rotating energy transfer. In variable speed wind turbines, the rotational speed is decoupled from the grid frequency by electronic converter. Thus, variation in grid frequency does not alter the turbine output power. With high wind penetration there is a risk that the power system inertial effect decreases, thus aggravating the frequency of the grid.

In solar power generation, the PV plant consists of the solar cell and DC to AC converter. Hence, they do not possess inertia and therefore cannot release energy to grid when frequency changes. This leads to frequency instability. Thus, with increasing penetration of inverter-connected power units, the rotational inertia of power systems is reduced and becomes highly time-variant as wind &PV shares are fluctuating heavily throughout the year. Frequency stabilization becomes thus more difficult.

B: UFLS With Renewable Energy

In extreme frequency decline situations, Under Frequency Load Shedding (UFLS) has been the only appropriate way to prevent a power system from collapsing [6]. Under frequency operation could be a huge threat to the secure and stable operation of a power system more so in the presence of RE at high penetration levels [12-15]. Therefore, the suitable amount of load should be shed as soon as possible to retain the power balance and prevent the frequency from falling below the specified value. The most common protection scheme that has been used in power systems for this purpose is UFLS [16]. UFLS schemes use the system frequency or its derivatives to determine the amount of power deficit and compensate it by several steps of load shedding [17-21].

The design of the general UFLS scheme considers the type of scheme, priority ranking of the feeders, equal geographic spreading and distributed generation[6].This has two drawbacks: First, conventional methods of UFLS schemes sheds a specified amount of load without considering the amount of power deficit. Thus, in most situations, the amount of load shed is more or less than necessary, resulting in serious cost implications and undesired damage. Again, with the integration of more and more RE into the grid, change in both load and generation makes the UFLS a complex issue. Thus, coming up with a design for UFLS with RE is becoming increasingly vital.

UFLS with PV: S. De Boeck and D. Van Hertem [7] considered ULFS with PV. The load shedding factors included in the implementation are load dependent setting, direction of current, periodic settings (seasonal/day and night) and smart grid approach (intraday). The same authors implemented the said factors in [8]. From these studies, it is apparent that installed PVs in the distribution grids should be taken correctly into account in the design of UFLS schemes so as to ensure that the disconnection of feeders due to a fault results in the disconnection of an amount of load close to the predefined value in the UFLS. Again, when disconnecting feeders with high local generation, both load and generation are disconnected, while only a limited part is actually useful. However other RE sources like wind were not put into account.

UFLS with Wind: Hong-Chan C et al [9] implemented a UFLS with Wind and battery storage devices (BSD) for isolated systems. PSS/E software was used to simulate the operating characteristics of the wind turbines generators (DFIGs). The optimal cost was based on thermal, wind and cost saving by using wind and RES. From the simulated results, it is clear that, if the off-island wind power generation is used effectively, off-island light load UFLS is improved, and RES is applied to heavy loads for peak shaving. However, there is no information on the kind of load shedding strategy employed.

H.T Zhang et al [10] dealt with combined under frequency and under voltage load shedding (UFUVLS) for a power system with low (5%) and high(30%) wind energy penetration. A modified IEEE 39-Bus England system built in Power Factory Dig SILENT was adopted for the validation. The simulated results clearly illustrate the insufficiency of examining frequency alone in protecting a power system from a fault. The UFUVLS strategy give practical result values as it considers examinations of both voltage and frequency in stability analysis.

UFLS with Wind and Solar: A. Ketabi and M. H. Fini [11] dealt with combined wind and solar UFLS using the method of frequency first derivatives(FFD). Single and multi-area systems were simulated considering four scenarios; islanded hybrid, decrease in solar irradiance during UFLS process, inertia constant variation and DFIG outages during

UFLS. Simulated results show that FFD is able to estimate the additional power deficit correctly(not accurately)during the UFLS process with RE(wind and solar) variations. However, load shedding due to voltage variation was not accounted for in the formulation.

From equations (3) to (7), the load shedding due to frequency change can be approximated by

$$\Delta P_f = \frac{\Delta H \frac{df}{dt}}{\Delta f} \tag{8}$$

The imbalance between generation and loads, ΔP, is defined by the *Modified Swing Equation(MSE);*

$$\Delta P = \frac{2}{f}\sum_{i=1}^{N} H_i \frac{df_a}{dt} \tag{9}$$

where H_i is the *Equivalent (Aggregated) Inertia* constant of the system, f_c is the frequency derivative immediately after disturbance or fault [2]

From Equation (1) and (8), the proposed load deviation due to change in frequency is thus given by

$$\Delta P = \Delta P_f \tag{10}$$

where ΔP_f is the total load triggered by under frequency relays.

B: Renewable Energy Storage (RS)

Here, we adopt the RES performance so as to design the optimal capacity which comprises of off-island system power consumption, Renewable Energy Storage(RS) life and the capacity of the inverters (DC-AC converters). The main objective is to determine the optimal cost, F which is equally divided into annual cost with reference to the data of the Kenyan Electrical Power Grid. To optimize RE (Wind and Solar in this case), RES is adopted and the generation cost is formulated as

$$F = \left[\sum_{i=1}^{8760} P_i \frac{15Ksh}{kWh} + \frac{2C_{inv+}3C_{bat+}}{15} - (12 * 365C_{bat} * P_{ro}(C_{bat}))\right] \tag{11a}$$

where C_{inv} is the cost of AC-DC converters with different capacities, C_{bat} is the price of different RES, $F_O = \sum_{i=1}^{8760} P_i \frac{15Ksh}{kWh}$ is the annual generation cost of an off-island thermal system , $F_{CS} = \frac{2C_{inv+}3C_{bat+}}{15}$ is the energy storage cost and $F_{RES} = 12 * 365C_{bat} * P_{ro}(C_{bat})$ is the annual cost reduction due to the RES.

Hence,

$$F = F_O + F_{CS} - F_{RES} \tag{11b}$$

It should be noted that wind is available throughout the day at different locations with varying speed while sunlight is available only for a particular duration of the day. The aim of introducing RS is to extract maximum amount of power from solar reactor during its available period (T_a). Some part of solar power generated during this period is stored using some available storage devices called RS in this paper. This stored power is delivered during unavailable period (T_u) of sunlight. The power extracted from the RES varies and can be considered as a variable (intermittent) load. Therefore this power ($PV_{ij,av} + w_{ij,av}$) is deducted from the total demand (P_D^t) and also the stored power (P_R) is added to it (duringT_a) or subtracted from it (during T_u)to obtain the actual demand(P_D^a)which is distributed among the available generating units. The dispatched amount of renewable power is limited to some part (x) of the total actual demand. The stored power is the difference of the total extracted and dispatched amount of renewable power during Ta. During T_u it must not exceed some part (y) of the total stored renewable power of T_a period. Moreover, the sum of total power delivered from the storage devices during T_u must not exceed the total power stored during T_a [23].Thus the constraints for the RS and RE variable generation can be defined as follows:

$$P_D^a = P_D^t - (PV_{ij,av} + w_{ij,av}) \pm P_R \tag{12}$$

$$(PV_{ij} + w_{ij})_d \leq xP_D^a \tag{13}$$

$$P_R \leq (PV_{ij,av} + w_{ij,av})_g - (PV_{ij} + w_{ij})_d \tag{14}$$

$$P_R \leq y\sum_{T_a}(PV_{ij,av} + w_{ij,av})_g - (PV_{ij} + w_{ij})_d \tag{15}$$

$$\sum_{T_u} P_R \leq \sum_{T_a} P_R \tag{16}$$

C: Combined Frequency with Renewable Energy Storage Cost (CFS)

The load shedding strategy adopted considers frequency, voltage and optimal cost. From equations (10) and (12), the Combined Frequency with Renewable Energy Storage Cost (CFS) Approach is thus given by

$$\mathrm{CFS} = h\Delta P + (1 - h)F \tag{17}$$

where h is the weighing factor for Load Deviation due to change in frequency and the cost of RS. For $h = 0$, there is best load shedding commitment (BOLSC) while for $h = 1$, there is best RE storage commitment (BSC).The optimal value of h corresponds to the level of RE penetration.

IV: SCENARIO BASED METHOD (SBM)

The probabilities of RE in each scenario are modelled using the scenario based method(SBM). For a general multivariate function, say, $y = F(X)$ where X is a vector containing the uncertain input values, the SBM uncertainty modelling is a method for finding the expected value of y. A set of scenarios, Ω_s is generated by *Roulette Wheeling Method (RWM)* for describing the probable values of X such that;

$$y = \sum_{s\epsilon\Omega_s} \pi_s F(X_s) \tag{18}$$

where π_s is the probability of state s.

Uncertainties and variability in RE power generation and load profile of the system, emerge into a probabilistic CFS which is formulated in this paper. The total cost of RS is given by

$$F_T = \sum_{S,t} \pi_s PP_s(t)\lambda_s \tag{19}$$

where F_T is the total cost paid , π_s is the probability of scenario s, $PP_s(t)$ is the power drawn from the RS in time t ,scenario s and $\lambda_s(t)$ is the price of energy obtained from the RS in time t ,scenario s($/MWh) and $C_i(P_i(t))$ is the production cost of the i^{th} thermal unit in time t.The objective function of a rational cost that is to be maximized is defined by

$$F = \sum_{S,t} \pi_s P_{D,s}(t)\lambda_c(t) - F_T \tag{20}$$

where $\lambda_c(t)$the price of energy in time t, and $P_{D,s}(t)$ is the load demand at time t and scenario. Equations (12) and (20) defines the dynamics economics of RS cost.

IV: THE KENYAN CASE

In Kenya, there has been increased penetration of RE especially wind and solar into the grid. On Tuesday 7th June 2016 at 1130Hrs, a nationwide black out hit the country for almost three hours when a monkey tripped at transformer at Gitaru Hydroelectric Power Station, leading to a loss of more than 180MW from the grid.

To analyze this case, the following information is required for the Kenya Bus System : (i)The load data(Both active and reactive) (ii)The generator data(inertia constant , transformer taps and machine reactance) (iii)Wind Turbines Generator information (Lake Turkana and Ngong) (iv)Solar generation (v)Transmission and distribution line data

The Kenyan case will be validated compared with the IEEE 39-Bus system which is commonly referred to as the 10-machine New-England Power System [22]. The one line diagram is as shown in Fig 1.0.

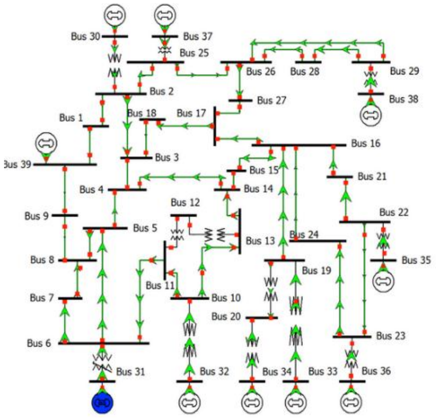

Fig 1.0 IEEE 39-Bus System [22]

V: CONCLUSION AND FUTURE WORKS

This paper has presented frequency stability with RES, Frequency Dynamics, RS economics using SBM and RE variability and UFLS. It is apparent that examination of frequency alone is not sufficient to protect a power system with high RE penetration from collapsing . Thus, a new approach called Combined Frequency with Renewable Energy Storage Cost (CFS) has been proposed for it considers both frequency and RE storage requirements. A tradeoff for load shedding and invoking RS incase of a fault is the formulated CFS. Further work in this area includes analysis of the Kenyan case of 7th June 2016 and adopting the same for an interconnected system.

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