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Optimal Load Shedding Scheme for a Model Renewable Energy Micro-Grid

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Abstract---Optimization of demand control in renewable energy micro-grids involves developing load shedding schemes and searching for the most optimum. With climate change campaign in favor of renewable energy micro-grids or integration to national grids, the stability of the systems becomes more unpredictable. Its therefore justified, technically and economically, to optimize both unit commitment plans to track the load curve closely and design load-shedding schemes that attain the voltage and frequency limits, while retaining maximum load on the grid. The study shows that through load-shedding, renewable energy micro-grids can be operated in the stable state at the expense of loads during times of severe power imbalances. Optimization of the load-shedding using PSO-GA technique ensure optimum amount of load is shed from the grid with each possible load shedding scheme getting evaluated first and selection of most effective scheme with priority for loads is accomplished.

Index Terms: **load shedding scheme, renewable energy, micro-grid, transient stability, under-frequency stability**

I. INTRODUCTION

Highly penetrated renewable energy grids or purely renewable energy micro-grids exhibit higher frequencies of network instabilities due to stochastic nature of loading and chaotic generation of power from unpredictable sources. These system instabilities are solvable by compensation techniques for voltage and frequency, which only apply when the available generation is capable of powering the connected loads, without violating the limits thereof. In cases where the generation is insufficient and power imbalances lead to violation of voltage and frequency limits, demand control is deployed as a measure of last resort.

According to Kenya National Grid Transmission Code/ Eastern Africa Power Pool, frequency fluctuations are regulated, such that when the grid is operating in the normal conditions, the frequency of operation ranges at ±1%, about the nominal frequency of 50Hz, i.e. between 49.5Hz to 50.5Hz. This frequency band is expanded to ±2% i.e. a range of between 49.0Hz to 51.0Hz about the nominal frequency, upon occurrence of disturbance in the network [1]. Once a major disturbance such as disconnection of large loads, failure of a major element in the transmission network or tripping of generating unit occurs, the frequency band can be expanded further up to ±2.5%, to range between 48.75 Hz to 51.25Hz. Extreme operational measures are taken after allowing a simultaneous occurrence of 2 or more major disturbances to operate with frequency ranges of -5%/+3% about the nominal frequency for a maximum of 20 seconds before extreme measures are initiated.

The main objective in this study was to model a purely renewable energy sources micro-grid, investigate its transient frequency stability and optimize the under-frequency load shedding scheme to achieve required levels of frequency and voltage fluctuations with minimum load disconnection and least cost for power storage, as formulated in the multi-objective function.

For a stable operation of a renewable energy micro-grid, controllable wind turbine/ solar plants need be resilient in fault ride through. The plants must provide active power that's proportional to retained voltages and maximizes reactive current supply during voltage dip while operating within its declared limit for at least 600 milliseconds or until voltage recovery to normal operating range. The plant should provide 90 percent of its maximum active power within 1 second upon voltage recovery.

Hybrid Particle Swarm-Genetic Algorithm is utilized to optimize the process of load shedding, in which the optimum possible combination of loads is selected, considering priority for the various types of loads i.e. industrial, commercial and domestic loads [2]. The renewable energy source generating units must remain connected for limits of: 0.5 Hz, rate of change of frequency, 20 seconds for frequency range of 47.0 to 47.5 Hz, 60 minutes for frequency ranges of 49.0 to 51.0 Hz and continuously operate at frequency range of 49.5 Hz to 50.5 Hz. Power imbalances that violate these conditions even after exhausting energy reserves option and compensation measures, will automatically initiate the prioritized load-shedding process [3].

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Major contributions in this work included considering the five components/ causes of demand control in a multi-objective formulation, as opposed to the single measurements of either voltage deviations, frequency fluctuations, energy storage, load flow/ losses and amount of disconnected load in restoring the grid into its normal operating conditions.

This paper is organized into five main sections: The first section, introduction, gives a background on the research while the second section describes related works (literature review) from different authors. A multi-objective problem formulation is outlined in third section with 5 sub-functions. In the fourth section, a detailed methodology, where an hybrid PSO-GA optimization technique is mapped into the problem, and on the last section, the results obtained from this study are analyzed and a conclusion is made on the sixth section.

II. LITERATURE REVIEW

[4] presented a fuzzy logic based demand control technique for shedding loads in an islanded distribution network, considering a major disturbance such as generator tripping. The developed fuzzy logic system technique utilizes load prioritization, rate of change of frequency and frequency levels to determine the most optimum loads for disconnection. Satisfactory stabilization is achieved, during generator tripping and on islanding operation.

[5] developed an under frequency load shedding scheme combining intelligent and adaptive techniques for both response based (frequency and its rate of change in the swing equation) and event based (power imbalance). The scheme is implemented in a islanded distribution network, whose investigations demonstrates improvements in frequence response of the network, with significant reduction of power deficiency effects during island transitions [6].

[7] considered parameters such as settling time, frequency deviation, nadir frequency and rate of change of frequency, in modelig the response of renewable energy power plants and developing frequency stabilization strategies. A thyristor switched lag compensator is used for improvemennts of frequency stability and optimization of the process is carried out using fire-fly algorithm. The results from this study indicate that frequency of parralled generation plants falls out of sychronism upon disturbance and low inertia turbine plants have least settling time and experience huge ROCOF and high frequency fluctuations.

[8] demonstrated the operation of an islanded mode grid, using intelligent load-shedding for power imbalances to stabilize voltage and frequency levels. Digisilent software is used in simulation of PLCs, in which the functions are embedded. The results affirm an efficient demand control for contingencies that are severe. [9] formulates a multi-objective function for restoration of voltage, considering cost of demand control, voltage deviations and power losses.

[10] Particle swarm optimization and its vectored form are used solution searches and comparatively found that EPSO has higher precision in shedding loads as compared to its conventional form. [11] analyzed challenges of high penetration of renewable energy sources in a grid and the required load shedding processes for stability restoration. The study considered multi-country approach for interconnected power systems, with high ranges of frequency dips. The main functions with respect to renewable sources included UFLS, primary control and system inertia. ENTSO-E guidelines were used.

III. PROBLEM FORMULATION

The multi-objective problem formulation is illustrated in equation (1), with five major sub-functions.

$$Min\,F = \{\varphi_1 VD + \varphi_2 LS + \varphi_3 FF + \varphi_4 NL + RE\} \quad (1)$$

The sub-functions include:

i) Energy storage for supply in times of deficiency (RE)
ii) Voltage Deviation Effects (VD)
iii) Frequency Deviation Effects (FF)
iv) Transmission and Distribution Losses (NL)
v) Disconnected Load for frequency recovery (LS)

The extent to which individual factors are co-related and magnitude with which they affect system stability is weighted using φ_n; where n = 1, 2, 3, 4 and 5.

Each of the sub-objectives is formulated as follows;

A. Disconnected Load for frequency recovery (LS)

Once power imbalances occur, such that demand exceeds supply, an optimal amount of load will have to be connected from the grid to ensure stability is restored. Equation (2) shows addition of individual power imbalances for the n generators in the network.

$$\textstyle\sum_{n=1}^{n} Pm_n - \sum_{n=1}^{n} Pe_n = \frac{2\sum_{n=1}^{n}\left\{H_n \frac{dfn}{dt}\right\}}{f_0} \quad (2)$$

In equation (2), ΔP_{ls} = disconnected load until frequency recovery, Hn = Nth generator inertia constant, and n= Number of generating machines in the network.

B. Voltage Deviations (VD)

In order to minimize destruction of equipment resulting

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from voltage violations the model micro-grid is developed with insulation levels according to IEC 60071-1 standard code, as indicated in table 1.0 below. Equation (3) constitutes the formulation of the sub-objective, in which V_m and V_j are the respective swing and j^{th} bus voltage levels during abrupt swings, VD= fluctuations in voltage and M is number of nodes.

$$VD = \sum_{j=1}^{M} \frac{(V_j - V_m)^2}{V_m^2} \tag{3}$$

Table 1.0 Insulation levels for model micro-grid equipment

Nominal/Rated Voltage	50 Hz, 1 minute WV	Lighting Surge	Highest operating voltage
220kV	395kV	950kV	245kV
132kV	275kV	650kV	145kV
66kV	140kV	325 kV	72.5kV

C. *Transmission and Distribution Network Power Losses (NL)*

Using the modified IEEE 9 Bus system with 3 renewable energy generators, a power flow solution based on equations (4) is carried out for power loss using NR method for transmission system. An additional distribution technical and non-technical power loss is provided for, ranging between 15 to 18 percent as per the World Bank 2019 report on energy efficiency for Kenya national grid systems. Active and reactive power losses in the network are formulated as in equation (4), where B = susceptance, G= conductance, M= total no. of network nodes and NL = network power losses

$$NL = \sum_{j=1}^{M} \sum_{i=1}^{M} \{V_j V_i (G_{ji} \cos\theta_{ji} + B_{ji} \sin\theta_{ji})\} \tag{4}$$

D. *Frequency Fluctuations (FF)*

During times of severe power imbalance, frequency fluctuations violating the specified limits of secure operation occur and are formulated in equation (5), in which H= inertia constant, PD= power demand, PG= available generation, f= frequency denotations nrm and f represent normal and faulty operation periods.

$$FF = 2\left[\left(\frac{H_{nrm}\frac{df_{nrm}}{dt}}{PG_{nrm} - PD_{nrm}}\right) - \left(\frac{H_f \frac{df_f}{dt}}{PG_f - PD_f}\right)\right] \tag{5}$$

E. *Renewable Energy Storage Cost (CRE)*

Renewable energy micro-grids utilize batteries for power supply during times of power imbalances. The facilities for storage and power conversions are, therefore, key in system stability. Their cost function is shown in equation (6), where C_{RESi}= Reduced cost of power not supplied due to available storage, C_{EAi}= Storage bank capital costs, C_{PGi}= fuel cost for supply storage power supply, P_i= Stored power, T= time period of study, CRE= cost of renewable energy storage.

$$CRE = \{\sum_{i=1}^{T} P_i (C_{EAi} - C_{RESi} + C_{PGi})\} \tag{6}$$

The multi-objective function of equation (1) is subject to constraints for load flow, generation capacity for active and reactive power, network node voltage levels, feeder current limits, optimum load shedding scheme constraints, allowable frequency limits, load priorities and capacity of battery banks and assumptions for coherence and dynamic equivalency, reducing the complexity of the transient stability analysis, the n-machine system is assumed coherent and reduced using equation (7), in which the inertia constants of individual machines are ramped together.

$$H_{eq} = \frac{H_1 G_1}{G_S} + \frac{H_2 G_2}{G_S} + \cdots + \frac{H_N G_N}{G_S} \tag{7}$$

Where Heq= Equivalent inertia constant, H1= Inertia constant of machine 1, G1= MVA rating of machine 1 and Gs = base rating and N denotes the number of machines.

IV. HYBRID PARTICLE SWARM – GENETIC ALGORITHM OPTIMIZATION

This hybridized version reaps three main benefits: first application of PSO for fitness function evaluation balances the exploration and exploitation processes in each iterations; second, high probability of crossing over in the partitioned sub-populations reduces the dimensionality and provides diversity and third, mutation operation rides through pre-mature convergence and snares of local minima. The adopted algorithm for optimization of the multi-objective function subject to constraints is outlined as follows;

i) Step 1: Initialize the population (partition variables, number of partitions, crossover and mutation probabilities, acceleration constants for the swarm and individual chromosomes and size of population)
ii) Step 2: Evaluate the fitness function for possible solutions/ search agents
iii) Step 3: Apply particle swarm optimization on whole population

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iv) Step 4: Apply selection operator of genetic algorithm on the population
v) Step 5: Partition the whole population into smaller sub-populations
vi) Step 6: Apply arithmetical crossover to each sub-population
vii) Step 7: Apply genetic algorithm mutation operator to the swarm
viii) Step 8: Update individual and global best positions
ix) Step 9: Iterate until the convergence criteria is met
x) Step 10: Print the solution and stop

The position and velocity of each particle is updated in every iteration according to equations (8) and (9), in which x represents the position of the particle, v represents the particle velocity, pb is the best position achieved by the particle, gb is the global best position, j denotes the iteration number, 0 denotes the previous iteration and 1 denotes the current iteration.

$$x_j^1 = x_j^0 + v_j^1 , \quad j = 1, 2, 3, 4 \dots P \tag{8}$$

$$v_j^1 = v_j^0 + \in_1 r_{jl}\left(pb_j^0 - x_j^0\right) + \in_2 r_{j2}\left(gb - x_j^0\right) \tag{9}$$

The crossover operation is done by first choosing a random set of β such that $\beta \in [0\ 1]$

Two offspring are generated from parents such that;

$$OS_j^1 = \beta pop_j^1 + (1 - \beta) pop_j^2 \tag{10}$$

$$OS_j^2 = \beta pop_j^2 + (1 - \beta) pop_j^1 \tag{11}$$

In equations (10) and (11), OS = offspring, pop= population and j denotes the iteration.

V. RESULTS AND ANALYSIS

A. *Model Micro-grid Transmission and Distribution (TD) Losses*

The transmission and distribution losses model considers load flow studies for the transmission network using the IEEE 9 Bus system, and considers distribution losses of 15 to 18 percent of the generation, according to distribution distances and voltage levels, as per the World Bank energy efficiency survey 2019. The resultant power loss profile is illustrated in the graphs of figure 1.0

B. *Transient Stability Swing Curve before Load Shedding*

Examining the transient stability of the renewable micro-grid with power imbalances as the key system disturbances, the swing curves of figure 2.0 are derived. These swing curves indicate severe instability that needs immediate load shedding to secure the system from frequency collapse.

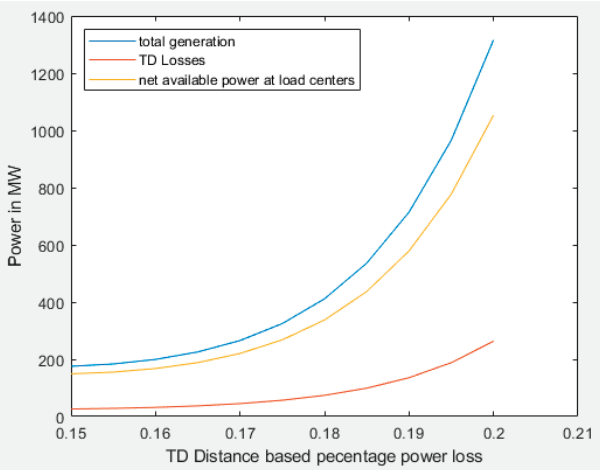

Figure 1 TD network losses for micro-grid model

C. *Prioritized Load Shedding Scheme*

After simulation, there are about 1500 possible combinations of loads, forming the population for optimization. These populations of possible solutions are evaluated using PSO-GA and the population which has best swing curve is selected and implemented. For a maximum power imbalance of 269MW, the optimum load combination constitutes of 12 loads and falls in the second stage of load shedding i.e. combines loads in domestic, agricultural and commercial categories and spares industrial category of loads as per the prioritization schedule. The total load disconnected for this imbalance is 295MW, consisting of 5MW, 6MW, 8MW, 10MW, 14MW, 16MW, 18MW, 23MW, 25MW, 31MW, 42MW and 97MW feeders.

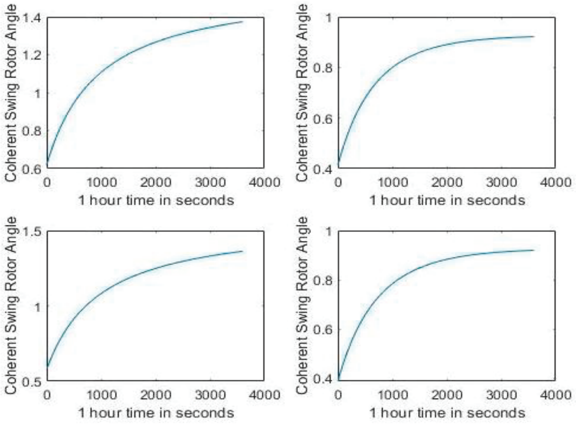

Figure 2 Severe power imbalance operation Swing

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D. *Transient Stability Swing Curve after Load Shedding*

The PSO-GA method is utilized to find the most optimal load shedding combinations. These optimal load combinations are then treated as faulty feeders and disconnected by switching off respective relays, thus relieving the micro-grid from adverse effects. The optimally restored stable system swing curves are indicated in figure 3.0.

VI. CONCLUSION AND RECOMMENDATIONS

An ideal solution for renewable energy micro-grids stability is to provide energy reserves sufficient enough to take up loads immediately after shedding, to avoid violation of consumer rights to universal access to energy for long periods. However, these reserves will increase cost of energy even during times of sufficient supply. A compromise is, therefore, required to ensure forecasting for availability of energy is integrated with reserve schemes and agreements in form of time and amount of energy with a trade-off for load-shedding in short periods of scarcity, as the only option of last resort, in securing the grid from collapse.

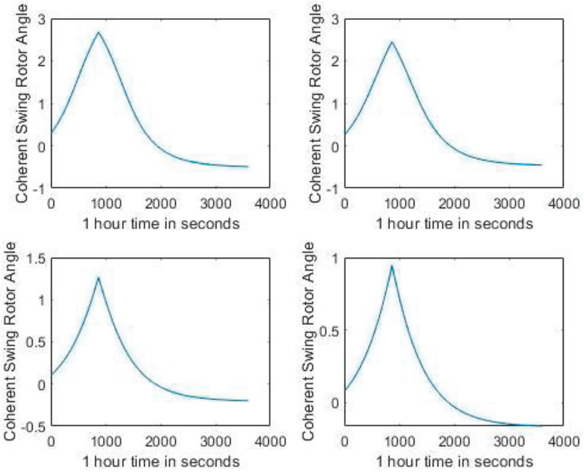

Figure 3 PSO-GA Optimized frequency recovery swing curves

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