STRATEGIC ENERGY MANAGEMENT OF A HYBRIDIZED WIND-SOLAR SMART GRID

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***Abstract*— Conventional power systems are transitioning to smart grids for remote control, reduced losses and auto correction of system faults. An energy management system for smart grids based on renewable sources is critical due to the intermittent nature of output power from these sources and variability of the load demands, which yield voltage and frequency fluctuations. This study analyses the superiority of smart grids based on power electronic transformers. P-F droop control method and Q-V droop method have been used for frequency and voltage rectification respectively. MATLAB simulations were run and the results show the hybridized smart grid has better stability as compared to stand-alone systems. The optimization method used is hybrid particle swarm and grey wolf due to its faster convergence performance and fast implementation process. The study finds that implementation of the management strategy modeled would result in 100% load supply and hence stability of the power system.**

***Index Terms* — Energy Management System (EMS), Power Electronic Transformer (PET), Renewable Distributed Generation (RDG), Wind-Solar System (WI-Se)**

I. INTRODUCTION

With an increase in the number of DC loads and energy demand in general, there is a need to provide clean and sustainable energy. Smart grids offer a more efficient and flexible mode of operation than ever before and are therefore the future [1]. To ensure optimum operation of the hybridized smart grid there is a need for development of a strategic energy management system (EMS). To develop a reliable EMS the interaction between the demand and load side of the grid must be well addressed. Renewable distributed generations (RDGs), mostly based on wind and solar, have become increasingly popular compared to the centralized generation. However, the power output of RDG is unreliable and unpredictable therefore there arises a need to develop an EMS to enhance reliability [1]. Previously, there has been energy management strategies developed for micro grids and hybrid micro grids but none for a hybridized wind-solar smart grid. This study will, therefore, develop a strategic energy management system which will lead to optimization of the hybridized solar-wind smart grid which will be based on the use of PET.

Due to depletion of energy resources globally, it is not only important to produce power in an intelligent manner, it's also critical to develop a proper EMS for the already existing renewable energy (RE) resources [1]. Distributed renewable energy resources (DRER) require more infrastructures for connection to the grid but offer a decrease in cost spent on transmission and minimize the distribution and transmission losses [1]. According to [2], there have been a few Energy Management Systems (EMS) for hybridized mini-grid developed in recent years. [2] Only dealt with an EMS for a mini-grid with the end game of a bi-directional power flow between the AC and DC micro-grids while [3] addresses a two level of control logic EMS for a micro-grid which is based on renewable as well as energy sources. The main purpose of using PET is to reduce power mismatches between the supply side and demand side and to minimize the voltage fluctuations on the DC bus in order to achieve stable high quality power between the two mini grids. PETs also facilitate provision of power to DC loads and AC loads simultaneously [2]. Connection to the grid of both mini grids is therefore made possible by PET

Contribution

To realize the full potential of RDGs, a system approach needs to be taken to categorize the load side and generation as a mini-grid [4]. In case of a fault, there is isolation to prevent any harm from the load side. The best way to actualize this is via smart grids, furthermore smart grids that are effectively managed. While there have been numerous researches done on EMS for mini-grids based on both renewable and non-renewable sources, none has been developed based on a hybridized solar-wind smart grid using PETs. This study addresses this gap and develops a strategic EMS for a hybridized wind-solar smart grid.

Paper Organization

The rest of the paper is organized as follows: Section II is the Literature Review, Section III is the Problem Formulation, Section IV is the Proposed Methodology, Section V is a presentation of Simulated Results, while Section VI is the work's conclusion and Recommendations in Section VII. Lastly, the references used are listed.

II. LITERATURE REVIEW

There has been a lot of research done previously on the management of mini-grids based on DRERs. Li, Sun, Dong and Zhang [2] in their work proposed a coordination strategy between the PET, the AC and DC mini grids and the batteries used in energy storage to effectively reduce the voltage fluctuations on the DC voltage bus. To ensure island protection against faults, the system has a circuit breaker which has a connection point to the DC micro grid in case of fluctuations of voltages past a certain critical point. There's a detailed structure of a single phase three stage PET as a means of power conversion between the two mini grids. The

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data on power of the system is gotten from the DC bus because the voltage on the AC bus is reflected onto the DC. In case of a rise or drop of the voltage, the PET controls the droop using the PET's second stage and a change exceeding a set value causes the system to go into a mode with constant voltage control. A curve on droop control with the PET and battery was drawn. An analysis of the operation was discussed as either charging or discharging. Design of the coordination strategy with development of different loads (balanced, heavy or light) was considered. This work proves the stability of the DC and AC micro grids through simulations using MATLAB to show the effectiveness of the control strategy by use of PET.

Jin, Dong and Wang designed a scheme which would aid coupling the ac and dc sub grids. Instead of using PET for the connection of the ac and dc mini grids, a BIC was used. The two aspects considered in the design of this scheme were economic enhancement and resilient enhancements. To achieve economic enhancement, power balance equality has to be realized as stated in [5]. The cost of the system was largely linked to the power produced by a DG and so analysis of each of the four DG was carried out. Costs due to frequency and voltage fluctuations were analyzed. . For resilient enhancement, the faulty operation of each DG was analyzed. The simulated data and graphs from MATLAB and Simulink validated the economical enhancement hypothesis of using the BIC in the system.

Gujar, Datta and Mohanty The work highlighted some of the initiatives put forward in India in the recent years such as ISGTF, a task force deployed to fast track the implementation of smart grids. [4] Analyses the diagram of a SMG based on distributed generation (DG) which incorporates special features such as integrating different DERs, centralized control of the SMG for optimization, resource profiling, load prioritization and the use of field programmable gate array (FPGA) a software that acquires the data and sends/receives the control signals to the mini-grid. The authors outlined the development of a dispatch controller for the SMG which communicates with a SCADA system through a GSM module and the applications of the SMG. In conclusion, the work addressed the applications of SMGs in based on RE resources in India.

III. PROBLEM FORMULATION

Capacity Credit (CC) defined as the contribution of each RE sources to enable the system realize adequacy is defined by effective load carrying capacity (ELCC), and equivalent firm capacity (EFC), which is the capacity form the generation side [1].

$$EFC = C^{fc} \tag{1}$$

$$R[C^{gc}; D] = R[(C^{gc} + C^{d} + C^{rf} - C^{rdg}); D] \tag{2}$$

And ELCC given by

$$ELCC = C^{rf} \tag{3}$$

$$R[C^{gc}; D] = R[(C^{gc} + C^{d} + C^{rdg})D + C^{rf}] \tag{4}$$

Where the amount of equivalent firm capacity is C^{fc}, C^{d} is the amount of load added to response to a demand, C^{gc} is the generation capacity of the system, R is the index of reliability and D is the level of loading.

Now, the power balance equations can be divided into three major sections: when there is balance between the load supplied by the SMG (wind, solar, and storage facilities) and the loads, when there power generated is more than that required by loads (light loads) and when the power supplied to the load is less than the required amount (heavy loads).

The balance mode (the voltage level on the DC bus is under normal conditions) power is given by [1]:

$$\sum P_{wind} + \sum P_{pv} + \sum P_{bd} \cong \sum P_{dcload} + \sum P_{acload} \tag{5}$$

Where Pwind is the output power of the wind mini grid, Ppv is the solar energy output and Pbd is the output of the battery storage facility while discharging normally [2].

Under the light load conditions (the voltage on the DC bus is above required level), the following equation is used [2]:

$$\sum_i P_{wind} + \sum_i P_{pv} + \sum_k P_{mbd} \gg \sum P_{dcload} + \sum P_{acload} \tag{6}$$

Where P_{mbd} is the maximum discharge rate power output of the storage facility.

Under the heavy load conditions (the DC Bus voltage is lower than critical value) [2]:

$$\sum_i P_{wind} + \sum_i P_{pv} + \sum_k P_{mbd} \ll \sum P_{dcload} + \sum P_{acload} \tag{7}$$

If the frequency on the AC bus voltage is under normal conditions, and the voltage on the dc bus is normal then [7]:

$$P_{wind} + \sum P_{pv} + \sum P_{bd} \cong \sum P_{dcload} + \sum P_{acload} \tag{8}$$

Applies.

If the frequency is too high or low then the equations (9) and (10) apply

$$P_{wind} + \sum P_{pv} + \sum P_{bd} \gg \sum P_{dcload} + \sum P_{acload} \tag{9}$$

$$P_{wind} + \sum P_{pv} + \sum P_{bd} \ll \sum P_{dcload} + \sum P_{acload} \tag{10}$$

It should be noted that droop control is much easier in the AC bus than in the DC bus [3].

The power contribution of each RE source is explained below. The solar energy is the output power given by the photovoltaic cells of the solar sub grid. It is given by the equation 11

$$Ppv = I_T \alpha (K[Tcell - Tr] + 1) \tag{11}$$

I is the incident radiation, alpha is a product of the panel's efficiency and packing factor. It's given as 0.11. K is a temperature coefficient set at 0.0047 while the reference temperature Tr is 25 degrees. The temperature of operation of the cell, Tcell, is given by:

$$T_{cell} = T_{air} + (0.0125NOCT - 0.25)S \tag{12}$$

NOCT is the nominal operating temperature and is given as 50 degrees, Tair is the actual temperature of the environment collected in the data, and S is the insulation rating given as 80mW per square centimeter.

For the Wind turbine energy [8]:

$$P_{wind} = \frac{1}{2}[Ceff(\alpha,\gamma) \times (\rho A)] \times {S_{wind}}^{3} \qquad (13)$$

Where P_{wind} is the electrical power output of the turbine, C_{eff} is the coefficient of the turbine performance, α is the ratio of the speed of the blade tip, γ is the pitch angle of the blade, ρ is the density of the air, A is the area the turbine sweeps, and S_{wind} the velocity of wind at a given time. C_{eff} is theoretically given as 0.48, for α =8.1 and γ is 0. ρ is given as 1.225 kg per cubic meter and A is the area of the turbine blade [8].

The objective function (in the case of power deficit and the case of surplus power) of the hybridized WI-Se is given as:

$$\mathrm{Obj\ Func(min)} = \sum \mathrm{P_{pv}} + \sum \mathrm{P_{wind}} + \sum \mathrm{P_{grid}} + \sum \mathrm{P_{batt}^{disch}} - \mathrm{Pdcload} - \mathrm{Pacload}] \qquad (14a)$$

$$\mathrm{Obj\ Func(min)} = \sum \mathrm{P}_{pv} + \sum \mathrm{P_{wind}} - \sum \mathrm{P_{injected}} + \sum \mathrm{P_{batt}^{charg}} - \mathrm{Pdcload} - \mathrm{Pacload}] \qquad (14b)$$

Where P_{pv} is the energy contribution of the PV cells given by equations (11) and (12) and P_{wind} is the energy contribution by the wind turbines given by the equation (13). P_{grid} is the power supplied from the grid in case of heavy mode, and $P_{injected}$ is the power injected to the grid in case of light mode. P_{EV}^{charg} is the power consumed by the batteries in case of charging mode. P_{batt}^{disch} is the power supplied by the batteries to the SMG in the discharging mode.

For droop control on the dc bus [4]:

$$f_{real} = f_{noload} + K_{fac}(P_{noload} - P_{real}) \qquad (16)$$

$$V_{real} = V_{noload} + K_{vac}(Q_{noload} - Q_{real}) \qquad (17)$$

Where Freal and Vreal are the frequency and voltage values of the AC bus. Pno_load and Qno_load are the real and reactive power values when the system is not loaded. K_{fac} And K_vac are the AC frequency and voltage coefficients given by [4]:

$$K_{fac} = \frac{F_{noload} - F_{minimum}}{P_{maximum} - P_{noload}} \qquad (18)$$

And

$$K_{vac} = \frac{V_{noload} - V_{minimum}}{Q_{maximum} - Q_{noload}} \qquad (19)$$

Fminimum for this system is the lowest frequency allowed on the Kenyan grid which is 49Hz and the Fmaximum is the highest value which in Kenya is 51Hz.

IV. PROPOSED METHOD

The SMG block diagram

The SMG bock diagram has been captured in Fig 1. The blue lines are the sensors from the Home load management modules transmitting to the control center while the green arrow is the sensor reading the state of charge of the batteries. The frequency on the AC bus will be transmitted via the sensor represented by red while the voltage on the dc bus is sensed by the brown line.

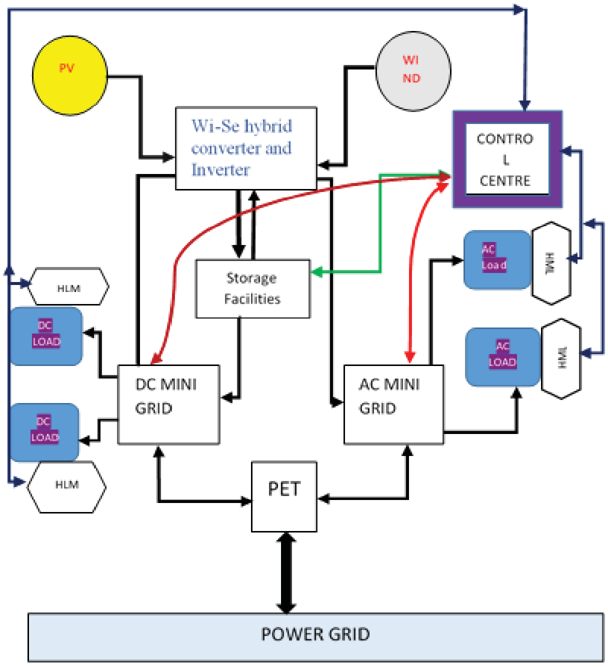

Fig 1: PROPOSED SMG BLOCK DIAGRAM

The system communication model has been developed as in Fig 2. It includes the control center checking for any change in system parameters autocorrecting them and updating the system.

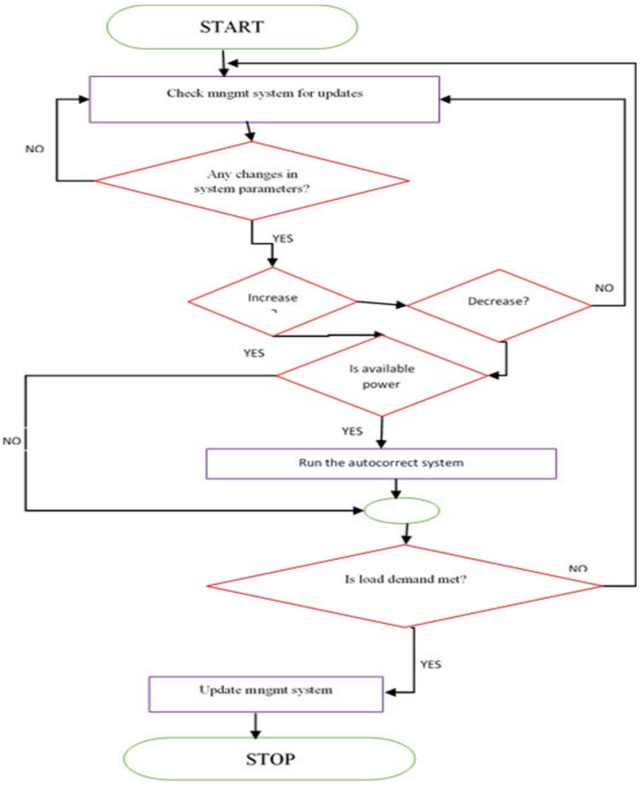

Fig 2: SMG CONTROL CENTER FLOWCHART

HPSO-GWO OPTIMIZATION METHOD

Optimization of SMG is a complex operation because of the intermittent nature of RE, load variability, and the production uncertainty. The purpose of this method is to manage RE based SMG and give optimum results. Recently, swarm intelligence [SI] techniques of optimization have become more popular as compared to traditional methods due to their diverse applications in different engineering fields. From previous works, the Grey Wolf optimization method has been used to optimize the developed hybrid mini grid [2] and the particle swarm optimization method has been used [9] and due to their advantages a hybrid of these two methods, hybrid grey wolf optimization and particle swarm optimization (PSO-GWO) [10] will be used in the optimization of the SMG management strategy developed.

The new governing equations (from the PSO) for the position and velocity vector are given as:

$$V_i^{t+1} = w * (V_j^t + C_1 R_1 (X_1 - X_j^t) + C_2 V_2 (X_2 - X_j^t) + V_3 (X_3 - X_j^t) \quad (15)$$

$$X_j^{t+1} = X_j^t + V_j^{t+1} \quad (16)$$

The alpha, beta and delta positions (from the GWO) are now defined by [11]:

$$D_\alpha = |C_1 X_\alpha - w * X| \quad (17)$$

$$D_\beta = |C_2 X_\beta - w * X| \quad (18)$$

$$D_\delta = |C_3 X_\delta - w * X| \quad (19)$$

The mapping of the parameters is as shown in table 1:

Table 1: SUMMARY OF MAPPED PARAMETERS

HPSO-GWO Parameters	**SMG Mapped parameters**
Search space	Available data variables (irradiance, temperature, wind speed, direction, humidity)
Search agents	Chosen data variables to be used in determining the optimum objective function
Position and velocity vector	Capability and speed of counteracting the instability and bringing the SMG back to stability
Search Agents	Storage facility(Batteries), RE sources (Wind and Solar), DC and AC sub grids, load profiles
Alpha, α	Wind energy output
Beta, β	Solar energy output
Delta, δ	Storage facilities (batteries)
Omega, ώ	National grid
Prey	Any imbalance in the SMG observed by frequency and voltage fluctuation
Fitness value	Present state of the potential stabilizing elements i.e. SoC of the batteries, frequency of AC grid, Vdc.

V. SIMULATED RESULTS

The solar stand-alone system power output as compared to the load profile comprising of both AC and DC loads is as depicted in Fig 3. Clear deficits of the solar system alone between the hours of 5PM and 8AM are depicted.

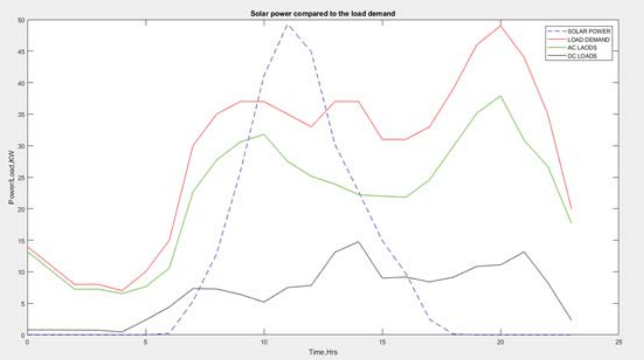

Fig 3: SOLAR STAND -ALONE POWER OUTPUT

The wind stand-alone system power output (with different turbine coefficients considered) as compared to the demand is also shown in Fig 4.

The figure shows the demand is not met during the day hours due to low wind speeds and the peak in supply occurs at night, when the demand, both ac and dc are low The turbine coefficients chosen were 0.59, Betz limit theoretical coefficient, 0.4 and 0.3. The turbines considered were small turbines for residential area of rating 400 watts to 100 KW.

The difference in the power production due to different coefficients is 32% decrease for the 0.4 turbine coefficient and 49% decrease when the 0.3 turbine coefficient is considered.

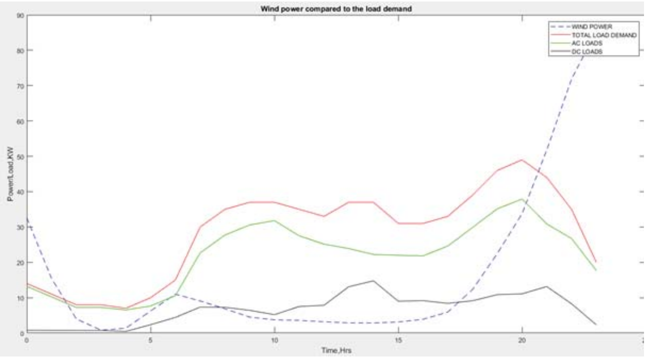

Fig 4: WIND STAND-ALONE SYSTEM POWER

Fig 5 displays the power output of the hybridized system against the demand the hybridized system meets the demand for most of the hours during the day (9 AM and 3 PM) and then again has a high output during the night. When compared to both solar and wind, the hybridized system meets more demand. During the day, the dips indicate the demand is not met hence there is a need to borrow from the national grid. The surplus power produced at night is injected (sold) to the national grid. In this manner, the system variations in frequency and voltage are minimized even when the power produced is more or less than the demand

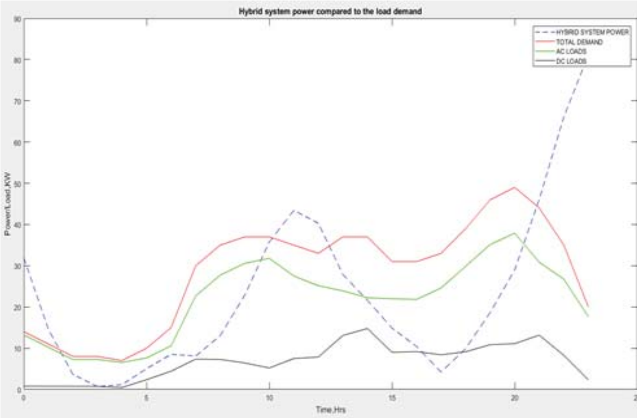

Fig 5: HYBRIDIZED SMG OUTPUT POWER

After optimization of the hybridized SMG system, the three systems deficits and surpluses were compared as shown in fig 6.

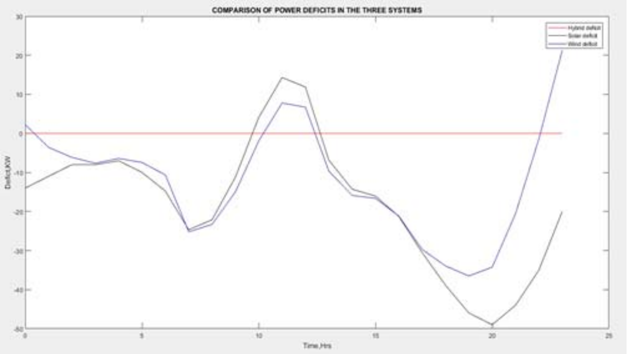

Fig 6: DEFICIT/SURPLUS AFTER OPTIMIZING

The hybrid SMG due to the energy management system developed and its optimization meets 100% of the loads based on Fig 6 and therefore has 0 deficits throughout the day. The maximum energy is injected to the grid while the minimum energy is borrowed from the grid. The frequency variations were recorded as: the minimum was 48.17 Hertz and the highest value was 51.06. The variations in the DC voltage were between 401.59V and 397.26V. These fluctuations (both voltage and frequency) were stabilized through the auto-correction system of the smart grid before supplying the loads or injecting to the grid.

The frequency and voltage fluctuation performance of the system before (blue curve) and after optimization (red curve) are shown in figs 7 and 8 respectively.

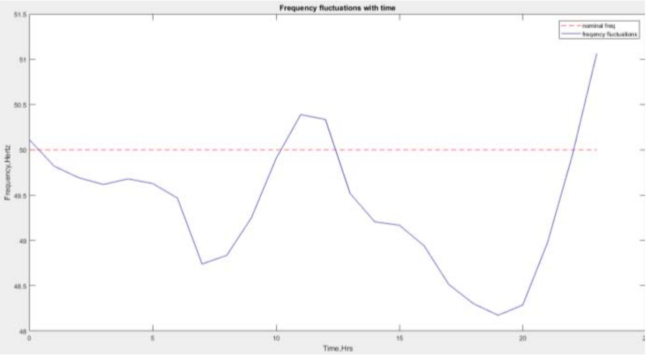

Fig 7: Frequency variations with demand variations in time

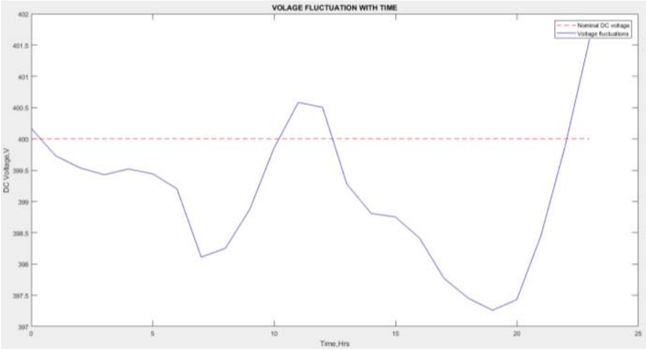

Fig 8: Voltage fluctuation with demand variations during the day.

VI. CONCLUSION

In conclusion the study of a hybridized solar wind smart mini grid based on power electronic transformers has been comprehensively covered in this project and an effective management strategy developed. The results indicate that a stand-alone wind system has an average percentage of 40.5 percent of meeting the demand while the solar stand-alone system has an average of 25 percent demand supply. The hybrid system has an average of 49% DC, 65% AC and an average of 57% demand supply before optimization and 100% demand supply throughout the day, after optimization using the PSO-GWO method. The frequency and voltage fluctuations were monitored and rectified using the P-F and Q-V droop control methods to ensure the variations are within 0-135% and 0-0.25% respectively. The energy management strategy developed ensures minimum borrowing of power from the national grid and sustainability of demand on the hybridized wind solar grid. In-case of surplus energy in the SMG, injection to the grid is effected to bring stability as well as reduce costs of the system.

VII. RECOMMENDATIONS

Implementation of tri-hybrid renewable energy systems. Addition of mini hydro system to the solar and wind hybrid systems would result in even better load supply and maximum efficiency and integration of load forecasting (both short term and long term) in smart grids.

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