Stand-alone microgrids

Citation for published version (APA):

Bauer, P., Weldemariam, L. E., & Raijen, E. (2011). Stand-alone microgrids. In *Proceedings of the Telecommunications Energy Conference (INTELEC), 2011 IEEE 33rd International, 9-13 October 2011, Amsterdam, The Netherlands* <https://doi.org/10.1109/INTLEC.2011.6099837>

DOI:

[10.1109/INTLEC.2011.6099837](https://doi.org/10.1109/INTLEC.2011.6099837)

Document status and date:

Published: 01/01/2011

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Stand-alone Microgrids

P. Bauer*, Leake E. Weldemariam* and Evert Raijen**

Delft University of Technology

PO Box 5

2600 AA Delft, The Netherlands

*P.Bauer@tudelft.nl, **e.raaijen@exendis.com

Abstract— A hybrid power system (HPS) which consists of diesel Genset, PV-arrays and wind turbines with energy storing and power electronic devices is discussed in this paper. An inventory of different connection topologies is made for some of the sources that generate AC power and others that generate DC power. By comparative study on the system efficiency, the Mixed-coupled HPS is found to be the best layout and this layout is used for further investigation. By considering AC-load demand, solar irradiation and wind speed profiles of a typical site, the sizing approaches of the system elements are developed for the HPS. For the selected layout, eleven innovative Power Management Strategies (PMSs) are defined; and for each PMS, Mathematical models are derived based on the power balance between the supply and the demand sides, charging/ discharging control of the battery and switching controls for the Genset.

The different HPSs are modeled using MATLAB/Simulink blocks and simulation results are analyzed. The different PMSs result to different sizing of system elements, power sharing, fuel consumption& environmental impacts, and cycles of batteries in the lifetime of the system. Finally, the hybrid system of each PMS is investigated for its cost competitiveness and environmental impacts by taking the economical aspects and fuel consumption into consideration. It is found that RESs and/or HPSs are cost competitive over the system life, in spite of the huge initial capital costs, for the variable costs of the Genset overshadows its low initial capital investment .

Keywords- Battery bank, Cost analysis, Diesel genset, Hybrid power system, Power electronics, Power management, Renewable sources

I. INTRODUCTION (HEADING 1)

THERE are many places, especially in developing countries, where about 33% of the world's population[1-2] do not still have access to electricity. These regions can be electrified either by extending the grids of the existing power systems or by constructing isolated new power systems, which are alternative energy sources. In general, it is preferred to go for the extension of the existing grids but they are not always affordable due to the fact that most of the non-electrified regions in developing countries are located in remote and difficult areas, like hilly regions, forests, deserts and islands, which demand huge investment for grid extension. In addition to this, the grid extensions are mainly distance dependent whereas hybrid systems are generation capacity dependent—hence the break-even “distance” is related to the demand [3] and this can be observed from Fig. 1. For remote places where electricity has not reached yet, it is recommended that decentralized generation, which is based on renewable energy

technologies, is perhaps the only efficient way to provide electricity.

Figure 1. Economical comparison of grid extension Vs PV hybrid systems

Using conventional energy sources (like diesel genset) is also another means through which these places can get electric supply. For the same reasons that make difficulty of extending the conventional grids, transporting fuel and replacement parts needed for the conventional sources like diesel generators in remote areas, renewable energy sources (RESs) are suggested to constitute the base of the electrical sources. The energy for RESs is locally available and properly chosen RESs can considerably reduce the operating periods of the conventional power sources which will result in the reduction of the fuel consumption and minimizing the need of maintenance. This in turn will result in the improvement of sustainable power generation. Over and above, diesel gensets as conventional energy sources are mostly used for fraction of the full load [4]. When gensets are not used at full load, they are less efficiently utilized and contribute in the polluting role of the environment.

A system which depends entirely upon RESs is possible but not reliable for the uninsured availability of the resources for the RES systems. In order to meet the sustained load demands during the varying natural conditions, RESs integrated with power electronics converters, energy storage devices& diesel genset as a backup source are studied in this paper. For the different types of power from the various sources, different connecting topologies are described in this paper. The first task is to determine the best layout. Then, answers to how the system elements are sized are described. The next question is to define different techniques in which the Genset could get supports from the RESs and the battery [5]. These are referred to as Power Management Strategies (PMSs). With each PMS, appropriate controls are designed in order to achieve the proper

switching of the genset and to control the charging/ discharging of the battery bank. In this paper, eleven different innovative PMSs are defined and their simulation results are analyzed. The cost analysis of each PMS is studied by considering the capital investment costs and variable costs.

II. CONNECTING TOPOLOGIES

In order to make a comparative study and select the best layout of a hybrid power system consisting of solar arrays, wind turbines and genset with battery bank, the following four topologies are considered (Fig. 2).

- Centralized AC-coupled HPSs- SCEN-1
- DC-coupled HPSs connected to grid via main inverter- SCEN-2
- Centralized DC-coupled HPSs- SCEN-3
- Mixed (AC/DC) coupled HPSs- SCEN-4

As it can be seen in fig. 2, the different topologies have the different sources connected in different ways. First, the paths of power flows from each power source are identified for the cases when the power is consumed directly or via the battery bank. When comparing the efficiency of power consumption, each power source is considered independently and the losses associated with the DC/DC converter with Maximum Power Point Tracker, Charging/Discharging of the battery and AC/DC converters are taken into account [9-10].

Figure 2. Proposed connecting topologies [1, 6-8]

Figure 3. Comparisons of power consumptions for different topologies

Depending on the ratio of directly consumed and stored power, there are different paths with different chains of converters. Fig. 3 shows the results of power consumption efficiency analysis with the directly consumed power of each power source introduced in the x-axis. When the power from PV-arrays is only considered, the efficiency comparison analysis in the four topologies gives that either SCEN-2, 3 or 4 gives the highest efficiency if not greater than 85% of the power is consumed directly (Fig. 3(a)). Fig. 3(b) shows the comparisons of the power consumption efficiencies with the different topologies when the power from the wind turbines is considered and SCEN-4 shows the highest efficiency of power consumption. In a similar fashion, the power from the diesel genset is independently considered for all the topologies and SCEN-2&4 gives the highest efficiency of power consumption as shown in Fig. 3(c).

The power consumption of each system takes the power consumption efficiency of all power sources into account. In all the three cases, where the powers from the PV-arrays, wind turbines and diesel genset are considered independently, SCEN-4 gives the highest efficiency of consumption and hence Mixed-coupling HPSs (SCEN-4) is the best choice of system layout and this is layout is considered for further investigation

III. SIZING OF SYSTEM ELEMENTS

The selected layout of HPSs includes different power sources, energy storing battery and power electronic devices. In this section, the sizing procedures of the system elements are reviewed.

To illustrate the methodology and analyze the system simulations of different PMSs which will be defined later, the average hourly load demand, solar irradiation and wind speed profiles shown in Fig. A(a) are considered in this paper and unit sizing of a PV-panel and a wind turbine are determined out of the renewable resources.

The output power from the solar irradiation on a single PV-panel referred to the DC-bus is calculated as [11]:

$$P_{pv}(t) = Ins(t) A_{pv} \eta_{pv} \eta_{dd} \quad (1)$$

Similarly, the power output from a wind turbine where referred to the DC-bus is found as [1]:

$$P_{wg}(t) = \frac{1}{2} \rho A_{rot} v(t)^3 C_p \eta_{ad} \quad (2)$$

With the help of equations (1) and (2), the hourly average powers from a PV-panel and a wind turbine corresponding to the irradiation and wind speed data (Fig. A(a)) are determined. By comparing the demand and the resources, the number of PV-panels forming PV-arrays and the number of wind turbines are increased to meet the demand.

The sizing of system elements depends on the load demand, irradiation and wind speed data and the type of PMSs used. With these data available, system elements are sized as follows.

A. Genset sizing

In this paper, the Genset which is supposed to be used when no other sources and energy storage are available is sized based on the peak load demand. Its nominal peak power capacity is at least equal to the peak loads demand.

$$P_{dg_{nom_peak}} = P_{load_{peak}} \quad (3)$$

For the different PMSs discussed in this paper, the sizes of the Genset are different according to the definition of each PMS.

B. Battery bank sizing

The preliminary size of the battery depends on the daily energy demand (KWh/day), DOA and DOD of the battery and is calculated as [12-14]:

$$BC_{calculated} = \frac{E_{load_{daily}}}{\eta_{bb}} \frac{DOA}{DOD} \quad (4)$$

The nominal battery capacity is usually 1.25 times the calculated value. For the different PMSs, the battery capacity is resized to the maximum energy it can charge in each cycle.

C. PV-array sizing

Once the unit size of a PV-panel is known from the solar power calculation using equation(1), the following cases are can be considered.

1) Only PV-arrays as power sources

If PV-arrays are the only power sources, the daily energy from the PV-arrays must at least be equal to the daily energy demand.

$$E_{pv_{daily}} \geq E_{load_{daily}} \quad (5)$$

From (5) it follows that the number of PV-panels forming the PV-arrays are:

$$N_{pv} \geq \frac{\int_0^T P_{load}(t) dt}{\int_0^T P_{pv_{panel}}(t) dt} \quad (6)$$

2) PV-arrays and Genset as the power sources

For this hybrid case, the Genset is first sized to the nominal power according to the definition of each PMS; and the daily energy demand must at least be met from the daily energies of the Genset and PV-arrays which can be described as:

$$E_{pv_{daily}} + E_{dg_{daily}} \geq E_{load_{daily}} \quad (7)$$

The numbers of PV-panels which form the PV-arrays by holding (7) true are:

$$N_{pv} \geq \frac{\int_0^T P_{load}(t) dt - \int_0^T P_{dg}(t) dt}{\int_0^T P_{pv_{panel}}(t) dt} \quad (8)$$

D. Wind turbines sizing

Once the unit size of a wind turbine is known from the wind power calculation using equation(2), the following cases can be considered.

1) Only wind turbines as power sources

If wind turbines are considered as the only power sources, the daily energy from the wind turbines must at least be equal to the daily energy demand.

$$E_{wg_daily} \geq E_{load_daily} \quad (9)$$

From (9) it follows that the number of wind turbines for this case are:

$$N_{wg} \geq \frac{\int_0^T p_{load}(t)dt}{\int_0^T p_{wg}(t)dt} \quad (10)$$

2) Wind turbines and Genset as power sources

When Wind turbines and Genset are sources, the Genset is first sized according to each PMS. The daily energy from the Genset and the wind turbines must at least be equal to the daily energy demand which can be expressed as:

$$E_{wg_daily} + E_{dg_daily} \geq E_{load_daily} \quad (11)$$

The numbers of wind turbines for this case that meets (11) are:

$$N_{wg} \geq \frac{\int_0^T p_{load}(t)dt - \int_0^T p_{dg}(t)dt}{\int_0^T p_{wg}(t)dt} \quad (12)$$

3) Solar-wind-Genset hybrid sources

For a Solar-Wind-Genset hybrid system, the Genset is sized firstly according to the techniques defined for each PMS. The daily energy demand must at least be met from the resources which can be described by:

$$N_{pv}E_{pv_panel} + N_{wg}E_{wg} + E_{dg} \geq E_{load} \quad (13)$$

For two variables (N_{pv} & N_{wg}) are unknown here, either of the following two assumptions can be used.

- Assume that the wind turbines and PV-arrays share the same energy (if found compatible) and the corresponding numbers can be determined as:

$$N_{pv} \geq \frac{1}{2} \frac{\int_0^T p_{load}(t)dt - \int_0^T p_{dg}(t)dt}{\int_0^T p_{pv_panel}(t)dt}, \text{ and} \quad (14)$$

$$N_{wg} \geq \frac{1}{2} \frac{\int_0^T p_{load}(t)dt - \int_0^T p_{dg}(t)dt}{\int_0^T p_{wg}(t)dt}$$

If the above assumption fails, assume the PV-panels or wind turbines and the unknown variable (say N_{pv} if N_{wg} is assumed) could be determined based on the energy balance equation(13) and is given by:

$$N_{pv} = \frac{\int_0^T p_{load}(t)dt - N_{wg} \int_0^T p_{wg}(t)dt - \int_0^T p_{dg}(t)dt}{\int_0^T p_{pv_panel}(t)dt} \quad (14)$$

E. Power converters

For the selected layout (Fig. 2(d)), there are two converters. The size of the DC/DC converter with MPPT mainly depends on the peak watt size of the PV-arrays and that of the inverter depends on the peak load demand. Normally, the DC/DC converter and the inverter are sized at 125% [12] of the peak PV-arrays and the peak load respectively.

IV. POWER MANAGEMENT STRATEGIES

For the selected layout of the connection topologies, eleven innovative PMSs are defined in this paper and they are compared for the sizes of the system elements and economic analysis. The system elements are properly sized following the sizing procedures [11-14]. The following simple electrical circuit model (Fig. 4) is used for the simulation of the PMSs and the power flow is based on power or current control [15] at the DC-bus.

First of all, mathematical models are derived for each PMS based on the power balance between the supply and the demand sides; the charging/discharging control of the battery and the switch control of the Genset each time it involves.

Figure 4. Simplified electrical model for the HPSs

The fundamental mathematical model which governs system operation is:

$$p_{load}(t) = p_{wg}(t) + p_{dg}(t) + p_{pv}(t) + p_{bb}(t)$$

$$U_{dc} = U_0 - R_i i_{bb}(t) \quad (15)$$

$$p_{bb}(t) = U_{dc} i_{bb}(t)$$

$$e_{bb}(t) = e_{bb_init}(t) - \int p_{bb}(t)dt$$

$$E_{bb_min} < e_{bb}(t) < E_{bb_peak}$$

For all PMSs, Simulation models are designed from the

described mathematical models using MATLAB/Simulink which corresponds to the block diagram representation shown in Fig. 5.

Figure 5. Block diagram of HPSs corresponding to Simulink model

In the system model (Fig. 5), the power from a single PV-panel and wind power corresponding to the average hourly irradiation and wind speed are used as input. The number of PV-panels and wind turbines vary with the types of PMSs. Charging/discharging and switching control models are included in the system model for the battery bank and the diesel genset respectively. The losses associated with the converters and batteries are also taken into account with the system simulations.

Applying the appropriate sizes of the power sources, the Simulink models are simulated to observe the power shares among the different sources and to see the amount of stored energy while the battery is charging and discharging each cycle. In this section, only summary of the PMSs will be given.

A. Only Genset (OG) PMS

In the OG PMS, the load demand is fully supplied from the diesel genset. This system is exactly the same as the case where the load is supplied from a conventional source and is taken as a reference. The Genset is sized to the peak demand of the load. The simulation of the Simulink model for this PMS gives the results in Fig. A(b).

B. Only PV-arrays partly supplying the load and partly charging the battery bank- OPB PMS

In this PMS, Only PV-arrays are used as power sources. ‘Charging/discharging control’ of battery is designed and the simulation of the Simulink model with properly sized system elements give the results shown in Fig. A(c)).

C. Only Wind turbines partly supplying the load and partly charging the battery bank – OWB PMS

For the OWB PMS, only wind turbines are used as energy sources and the battery bank is used to store energy when supply exceeds the demand so that the stored energy could be used at times of higher demand. The simulation of properly sized system elements for this PMS gives the results shown by Fig. A(d).

D. PV-arrays and Wind turbines partly supplying the load and partly charging the Battery bank- PWB PMS

With this operating mode, the RESs (PV and Wind) are the only energy sources for the system. They provide the power demand of the load throughout the cycle. The simulation of the Simulink model for the PWB PMS gives the results on power

share and stored energy during each cycle as shown in Fig. A(e).

E. Renewable Power sources with Battery bank& Average Genset power in the presence of a load – RBAG PMS

This is one of the strategies in hybrid mode of operation for which the Genset is controlled to operate at the average load ($P_{dg_{peak}} = P_{load_{ave}}$) in the presence of demand, and the RESs with the battery bank are sized such that the demand is fully supplied. Simulink model for the RBAG PMS is designed and system elements are properly sized. The simulation of the Simulink model gives the power share and stored energy results shown by Fig. A(f).

F. Renewable sources with Battery bank& Average Genset when the demand exceeds the average load - RBA⁺G PMS

This PMS is a modification of RBAG PMS in such a way that the switching of the Genset is controlled so as to operate at average load ($P_{dg_{peak}} = P_{load_{ave}}$) only if the demand is greater than the average load. New Genset control is modeled and the system elements are differently sized than the earlier RBAG PMS. By incorporating the modifications, simulation of the Simulink model gives results of power share among the power sources and the energy stored in the battery during each cycle. The results are shown by Fig. A(g).

G. Peak Power Shaving (PPS) PMS

This is another hybrid mode of strategy where the Genset gets support from the RESs and battery banks. In this paper, the PPS PMS is defined for which the Genset switches onto operation when peak demands appear in the operation and the Genset supplies only portion of the demand distinguished at $p_{load}(t) - K \cdot p_{load_{peak}}$ for a setting factor K. The Genset size for this PMS is $P_{dg_{peak}} = (1 - K)P_{load_{peak}}$. The simulation results of the Simulink model for this PMS are shown in Fig. A(h).

H. Maximum ON/OFF (MOO) PMS

With this PMS, the Genset is controlled to operate at its maximum capacity ($P_{dg_{peak}} = P_{load_{peak}}$) when the load demand is greater than a setting point, K otherwise it remains OFF.

The remaining portion of the demand is supplied from the RESs with the battery bank. With the appropriate sizes of system elements in this PMS, the Simulink model is simulated and the resulting power shares and stored energy are shown by Fig. A(i).

I. Renewable sources with Battery bank supplying any load less than the Average demand – RBA PMS

This is the case for which demands up to the average load are supplied by the RESs together with the energy storage and the Genset is controlled to supply the remaining portion of the demand (demand above average). The nominal Genset size

is $P_{dg_{peak}} = P_{load_{peak}} - P_{load_{ave}}$. The Simulink model of RBA PMS is simulated and the results are shown by Fig. A(j).

J. Genset operating at Base load in the presence of a load – GB PMS

This is another hybrid mode of system operation where the Genset gets support from the RESs and the battery. Genset

(a) Load, irradiation & wind speed profiles

(b) results of OG PMS

(c) results of OPB PMS

(d) results of OWB PMS

(e) results of PWB PMS

(f) results of RBAG PMS

(g) results of RBA*G PMS

(h) results of PPS PMS

(i) results of MOO PMS

(j) results of RBA PMS

(k) results of GB PMS

(l) results of GBA PMS

Figure A. Considered load demand, average hourly irradiation and wind speed profiles, (b) –(l) Power shares and stored energies of the simulation for different PMSs

control is designed to operate it at the base load in the presence of the demand $P_{dg_{peak}} = P_{load_{base}}$. The simulation results for this PMS are shown in Fig. A(k).

K. Genset operating at Base load or Average load – GBA PMS

This is modified hybrid mode of operation by combining the concepts of RBA^+G and GB PMSs. For this PMS, Genset control is designed to make it operate at base load (if demand is less than average load) or at average load (if the demand is greater than average load). The nominal Genset size is $P_{dg_{peak}} = P_{load_{ave}}$. The RESs with the storage device are sized properly to supply the remaining portion of the load demand. The Simulink model for GBA PMS is simulated and the results on the power share and stored energy are depicted as shown by Fig. A(l).

V. ANALYSIS OF SIMULATION RESULTS

In this paper, eleven types of innovative PMSs are defined. For each PMS, mathematical equations describing the system operation are derived; the system elements are properly sized; control models are designed for the Genset (if it involves) and battery bank. Simulink models are then designed for each PMS. The simulation of the Simulink models for the results of power share and stored energy are indicated in Fig. A(b) through Fig. A(l). The following points summarize the results of the simulations.

- The simulation results of in all PMS verify that the power balance always holds true. The instantaneous power at the supply side equals the power at the demands side. The power at the supply side is the sum of the power shares among the different power sources which depend on the definition and type of each PMS.
- For the different PMSs defined in this paper which result into different contribution of power from each source, the sizes of each system elements are different. Fig. 6 shows the maximum power sizes of system elements in each PMS defined in this paper.
- In each of the PMS where the Genset involves, different models are designed for switching the Genset ON and OFF based on the load demand and the energy level of the battery. Comparing the simulation results with the mathematical model descriptions for each PMS, the ‘Genset controls’ are performing as required.
- The ‘Charging/discharging control’ model of the battery bank operates well in controlling the battery from not overcharging and under-discharging. This is observed from the energy curves of each PMS, and the battery charges to below the maximum capacity limit and discharges to above the maximum DOD (70%).
- The battery bank is preliminarily sized based on the daily energy demand. When applied to the different PMSs, it is found that the battery is not fully utilized at its preliminary size. Fig. 7 shows the comparison of the

battery sizes when it is preliminarily sized and when it is resized to the maximum energy it can charge during each cycle for each PMS (Fig. A(b) - Fig. A(l)).

- The degrees of active charging/discharging (DOD) of the battery with each PMS are different showing that the lifecycles of the battery are different. For valve regulated lead acid battery [16], the DOD for the different PMSs are calculated and the corresponding estimated numbers of cycles are compared as shown by Fig. 8 (numbers on the bar graphs are the cycles).
- The efficiency of energy utilization of the battery within the different PMSs is another important point to be noted from the energy curves. The fact that the energy levels at the beginning& ending of each cycles are the same indicates the efficient utilization of the stored energy, hence no excess and unusable energy from a given cycle are available for the next cycles.
- Losses across the DC/DC converter with MPPT, AC/DC converter and charging/discharging of the battery are considered when sizing system elements and designing the system Simulink models.

Figure 6. Maximum power sizes of power sources in each PMS

Figure 7. Comparisons of preliminary & resized battery sizes for each PMS

Figure 8. Comparisons of DODs and cycles of batteries with the PMSs

VI. SYSTEM OPTIMIZATION

Different techniques where the Genset gets supports in supplying the demand are defined and explained in this paper. To find the most optimal strategy, the impacts of the Genset on the environment, the components lifetime and the capital& lifetime costs regarding to each PMS are analyzed in this section.

A. Fuel consumption

The daily fuel consumptions of the Genset with each PMS are calculated by the 'Genset fuel consumption' subsystem of the system Simulink models and the results for all PMSs are shown by Fig. 9. The environmental effects are associated with the fuel consumption of Gensets. The more Gensets consume diesel fuel, the more polluting gases they release and the higher is their impact on the environment.

From Fig. 9, the OG PMS shows the highest cyclic fuel consumption followed by RBAG and then GBA PMSs. Hence, the impacts in polluting the environment are in the same order. Among the hybrid PMSs defined in this paper, the PPS PMS shows the least fuel consumption and hence the least pollution effect followed by RBA and GB PMSs.

B. Capital investment costs

The capital cost (CC) of the system consists of the initial capital investment of all equipment, expenses on the system design, transportation, engineering, installation and the likes. This cost is always considered as a single payment occurring in the initial year of the project, regardless of how the project is financed. Detail economic calculations are performed and only summary of the analyses are given here. Fig. 10 indicates the initial capital investments of each system elements constituting the system corresponding to each PMS.

Figure 9. Comparisons of fuel consumptions for each PMS

From Fig.10, it can be deduced that:

- The capital investment of the Genset (in all PMSs where it involves) is by far smaller when compared with the capital investments of RESs.
- The OG PMS requires the least initial capital investment followed by RBAG PMS. The PMSs with

relatively high power share from the Genset require small initial capital investment.

- The PV-arrays and wind turbines require highest capital investments in the OPB and OWB PMSs respectively, and contribute high shares to the capital investment costs with the other hybrid PMSs they involve.
- The PMSs with only RESs (OPB, OWB or PWB PMS) require huge capital investment costs. Hybrid PMSs with large power share from the RESs indicate the requirement of high capital investment than the case where large power share is from the Genset.
- The PMSs with the same and preliminary sized battery bank show huge capital investment costs on the battery banks than PMSs with resized battery banks.

Figure 10. Comparisons of capital costs system elements for each PMS

C. Variable costs

The variable costs (VC) are expenses which depend on the lifetime span and vulnerability of the system components and the lifetime of the system. These costs include operation& maintenance cost (OMC), replacement cost (RC) and fuel cost (FC). The detailed analysis on VCs can be referred in [17] and Fig. 11 depicts the comparisons of VCs among systems of different PMSs and system elements constituting them.

The analysis on the variable lifetime costs indicates the following points.

- The Genset subsystem in all PMSs it involves requires huge variable cost for its continuous fuel consumption, relatively higher operation and maintenance costs, and replacements every 10 years of system life.
- The OG PMS requires the largest VC among all PMSs defined in this paper.
- The VCs of only RESs are very small for no replacements are considered in 20 years of system life, and also relatively small maintenance and operation costs are required.
- The DODs of the battery bank with the different PMSs determine the lifecycles of batteries and thus the

number of replacements required in the lifetime of the system.

- The PMSs with more power contribution from the Genset show large variable costs, in general.

Figure 11. Comparisons of variable costs system elements for each PMS

D. Life-cycle cost

The life-cycle cost (LCC) includes all expenses incurred over the life of the system. The LCC analysis comprises the variable lifetime costs (VCs) in addition to the capital investment costs (CCs). Analysis of LCC is very important to compare the different power management options and to determine the most cost-effective system design in the system life. Detailed analysis about LCC can be referred in [17] and Fig. 12 depicts the comparisons of the LCCs for the different PMSs.

From Fig. 12, the following points can be summarized.

- PMSs with large power share from RESs require huge initial capital costs but small lifetime variable costs.
- PMSs with large power contribution from the Genset require small initial capital cost but large variable costs.
- PMSs with only RESs and/or hybrid sources are cost competitive over the system lifetime despite the huge capital investment costs of renewable sources. In other words, the continuous fuel consumption, replacement costs and operation& maintenance costs, which adds up to the initial capital costs to give the total life-cycle cost of the conventional sources (Genset), overshadows the lower initial capital costs of Gensets.

Figure 12. Comparisons of life-cycle costs of system elements for each PMS

VII. CONCLUSION

Hybrid power system which consists of diesel Genset, PV-arrays and wind turbines with energy storing device and power electronic devices is investigated in this paper by finding the most efficient configuration layout. It is found that with the Mixed-coupling HPSSs, best efficiency of power consumption can be achieved when compared with the other topologies and this is chosen as the best layout. The selected layout is applied for further investigation to achieve an efficient and cost competitive strategy so that hybrid power sources could improve the life of people especially in rural areas where electricity from the main grid has not reached yet.

With typical AC-load, solar irradiation and wind speed profiles of a typical site, the sizing approaches of each energy sources, the battery bank and power electronic devices are developed. Having defined the preliminary sizing approaches of system elements for the selected topology, eleven different innovative power management techniques, where the diesel Genset gets supports from the renewable energy sources and the battery bank, are studied. For each PMS, mathematical models are developed based on the power balance between supply and demand, charging/discharging control of the battery and the switching controls of the Genset.

The different systems which resulted from the defined PMSs are modeled using MATLAB/Simulink blocks. 'Charging/discharging control' of the battery and 'Genset control' are included in the designed Simulink models of each PMS. The appropriate sizes of system elements are applied to each PMS and simulation results are analyzed by considering the power shares and energy stored in the battery each cycle. The simulations verify that the results are in accordance to the mathematical modeling which depends on the governing energy and power equations. The demand is always met and the charging/discharging of the battery is controlled between the upper and lower limits. The proper sizing of system elements results in the efficient utilization of the power from the renewable sources and the battery bank. It has been also observed that the sizes of the different energy sources, DODs and thus the lifetime of the battery banks are affected with the different PMSs. This in turn, brings about different numbers of replacements of the batteries which incur additional cost. Batteries with high DOD require replacements before the end of the lifetime of the HPS.

Finally, the hybrid system with the selected topology is investigated for optimization. The different PMSs result in different fuel consumption by the Genset and this in turn results into different impacts on the environment. The OG followed by RBAG and then GBA PMSs show the highest cyclic fuel consumptions in the same order. For this reason, it can be concluded that these PMSs also have the largest impact in polluting the environment. The study of the cost analysis is performed in three steps. The capital investment costs are performed for each PMS firstly. The only RESs PMSs (OWB, OPB and PWB PMSs) require huge capital investments and the OG PMSs require the least initial capital cost. Secondly, the variable costs are investigated over the lifetime of the system. The renewable sources (PV-arrays and wind turbines) and the power converters require no replacements and little operation

and maintenance costs. The battery banks require replacement costs, depending on the PMSs where the DOD of the battery bank is affected, in addition to some operation and maintenance costs. However, the Genset requires continuous fuel supply resulting in huge fuel cost over and above to the relatively high operation & maintenance costs and replacement costs over the system life. From the defined PMSs, the OG followed by RBAG and then GBA PMSs show the highest lifetime variable costs over 20 years of system lifetime

By combining the capital costs with the variable lifetime costs, the life-cycle costs of the systems for the different PMSs are analyzed and it is found that the renewable energy sources and/or the hybrid sources are cost competitive over the system lifetime despite the huge capital investment of the renewable sources. In other words, the continuous fuel consumption costs, replacement costs and operation & maintenance costs, which adds up to the initial capital costs giving the total life-cycle cost of the conventional sources (Genset), overshadows the lower initial costs of Gensets.

REFERENCES

- [1] Osama Omari, Egon Ortjohann, Alaa Mohd, and Danny Morton, "An Online Control Strategy for DC Coupled Hybrid Power Systems," in *2007 IEEE Power Engineering Society General Meeting*, Tampa, FL, 23 July- 2007, pp. 1 - 8, ISSN:1932-5517, ISBN:1-4244-1298-6
- [2] N. Phuangpornpitak and S. Kumar, "PV hybrid systems for rural electrification in Thailand," *Renewable and Sustainable Energy Reviews*, *ScienceDirect*, vol. 11, Iss. 7, pp. 1530-1543, September 2007.
- [3] Alliance for Rural Electrification (ARE) - shining a Light for a progress, "Hybrid power systems based on renewable energies- A suitable and cost-competitive solution for rural electrification", www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/Positi on_papers/ARE-WG_Technological_Solutions_-_Brochure_Hybrid_Systems.pdf
- [4] J. Leuchter, P. Bauer, V. Řefucha, V. Hajek: Dynamic Behaviour Modeling and Verification of Advanced Electrical-Generator Set Concepts, *IEEE Transaction on Industrial Electronics* 2009, Volume 56, Issue 1, January 2009, ISSN: 0278-0046, pp.266-278
- [5] D. Lu and B. François, "Strategic framework of an energy management of a microgrid with a photovoltaic-based active generator," in *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium* Lille 1-3 July 2009 pp. 1-6
- [6] Mike Meinhardt, Martin Rothert, Michael Wollny, and Alfred Engler, "Pure AC-Coupling –The Concept for Simplified Design of Scalable PV-Hybrid Systems using Voltage/frequency Statics Controlled Battery Inverters."
- [7] Ahmed Agus Setiawan, Yu Zhao, Rob Susanto-Lee, and Chem. V. Nayar, "Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse Osmosis desalination plant for remote areas," *Renewable Energy-Elsevier*, vol. 34, Iss.2, pp. 374-383, February 2009.
- [8] Gajanana Hegde, Pratap Pullammanappallil, and Chem Nayar, "Modular AC Coupled Hybrid Power Systems for the Emerging GHG Mitigation Products Market," in *IEEE-Centre for Renewable Energy & Sustainable Technology*. vol. 3 Perth, Australia, 15-17 October 2003 pp. 971-975, ISBN:0-7803-8162-9.
- [9] D. Lu and B. François, "Strategic framework of an energy management of a microgrid with a photovoltaic-based active generator," in *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium* Lille 1-3 July 2009 pp. 1-6
- [10] Dylan Dah-Chuan Lu and Vassilios G. Agelidis, "Photovoltaic-Battery-Powered DC Bus System for Common Portable Electronic Devices," in *IEEE Power Electronics Specialists Conference (PESC) 2008, Greece*. vol. 24, February 13, 2009, pp. 849-855.
- [11] D.B. Nelson, M.H. Nehrir, and C. Wang, "Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems," *Renewable Energy-ScienceDirect*, vol. 31, Iss. 10, pp. 1641-1656, August 2006
- [12] Mukund R. Patel, "Wind and Solar Power Systems". Kings Point, New York: CRC Press LLC, 1999, ISBN: 0-8493-1605-7.
- [13] IEEE, "IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems." vol. IEEE Std 1562™-2007 New York, USA, 12 May 2008.
- [14] IEEE, "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems." vol. IEEE Std 1013-2000 3 Park Avenue, New York, NY 10016-5997, USA, 30 March 2000.
- [15] ZHOU Tao, LU Di, FAKHAM Hicham, and FRANCOIS Bruno, "Power flow control in different time scales for a wind/hydrogen/supercapacitors based active hybrid power system," in *Power Electronics and Motion Control Conference, 2008 (13th EPE-PEMC 2008 IEEE)* Poznan 1-3 Sept. 2008, pp. 2205 - 2210
- [16] BAE SECURA PVV CELL Solar, "Technical Specification for Valve Regulated Lead-Acid Batteries (VRLA)" BAE Batterien GmbH, Ed. Berlin, August 2008.
- [17] Mohanlal Kolhe, Sunita Kolhe, and d J. C. Joshi, "Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India," *Energy Economics incorporating Journal of Energy Finance & Development*, vol. 24, Iss.2, pp. 155-165, March 2002.
- [18] Freek Baalbergen, P.Bauer: Power Management Strategies for Generator-set with Energy Storage for 4Q-load, *IEEE Transaction on Industrial Electronics* Volume 56, Issue 5, May 2009, ISSN: 0278-0046, 1485 – 1498