Energy efficiency enhancement of off-grid photovoltaic (PV) power plant

Sibusiso B. Dlamini[1], Emmanuel Bakaya- Kyahurwa[2], Peter M. Mashinini[3]

Abstract — The sizing of the off-grid PV systems is currently based on a manual approach, i.e. daily load is estimated by identifying commonly used load appliances for modelling system performance. If the system is not properly sized, it may not function according to expectation. The purpose of this paper is to present a conceptual design of an off-grid (autonomous) photovoltaic (PV) power plant, fitted with an efficient power regulating (EPR) management system of solar batteries and an instinctive solar tracking of PV panels. An optimization model for an Efficient Power Regulating (EPR) system of solar batteries was coupled to a solar tracking device so that the PV panels were constantly in full view of the sun. The objective function of the model was to maximize the efficiency of PV cells through PV battery charge regulation and load control in off-grid PV installations. This study revealed that the effectiveness of the EPR of solar battery (SB) when totally discharged can be realized when the accumulating battery (AB) charge reaches 50%.The study findings were indicative of the effectiveness of the EPR of SB. Hence, the EPR technique and the automatic tracking of PV solar panels proved to be the most effective technique of optimizing the energy efficiency of autonomous PV power plants.

Keywords: Autonomous Photovoltaic (PV), PV solar battery, Energy efficiency, PV solar panel.

1. Introduction

Improvement of off-grid photovoltaic power plants depends primarily on the increased quality of the technical characteristics of power plant sources - solar and the accumulating storage batteries (SB, AB). However, even with the most innovative sources of energy power plants which are currently available, the independent power plant facility may have a compromised power output characteristic due to the irrational usage of their potential capability (Sharma, 2011). Therefore, when designing contemporary and efficient stand-alone PV power plants, it should be undertaken in such a manner that it is able to address two major chores, these are;

- The development and usage of solar cells with increased efficiency and batteries with improved performance.
- The task of PV system design of power plants with the aim of improving their energy efficiency.

In this paper, the EPR is proposed for solar cells in order to enhance efficiency of PV plants and a technique for PV battery charge regulation and energy load control in off-grid PV plants is presented.

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2. Brief background

The effectiveness of the usage of PV energy sources in their long-term operational cycle, to a large extent depends on the block diagram, design and acknowledged conducts of managing energy sources (Shinyakov, 2007). At present, widely employed are block diagrams of energy systems and plants without the consciousness of the technique of instigating an efficient practice of the regulation of its power (source, n.d.). A number of autonomous PV power plants mostly employ simple controls of current charge and discharge of the AB, which simply cut off the source of energy of SB when the voltage at the AB reaches its limit. However, by reducing the voltage on AB to a certain level such that a solar cell is reconnected again and charging is resumed, voltage on SB is determined by the voltage of AB at a specific given moment, depending on the state of charge of AB. Since EPR management system is not realized, consequently the rate of energy efficiency of such PV power plants is minimal.

3. Methodology

Maximizing the energy efficiency ratio of autonomous PV power plants not less than 30-50% is possible through the following basic means (Shinakov et al., 2010):

- Realizing of the power intake mode at the optimal operating point of the current-voltage characteristics of the solar battery during the life of its exploitation (realizing of the method of efficient regulating of power of solar battery);
- Realizing of a continuous mode of automatic tracking of PV panels for the sun;
- Optimization of the solar battery structure in order to achieve a minimum heating of photocell elements.

3.1 Efficient power regulating management system

The effect of the realization of the EPR of solar batteries depends on a range of variations in the operating temperature of PV panels. Solar batteries of PV stand-alone power plants are used at significantly varying operating conditions. They are strongly influenced by the environment. Their current-voltage (V-I) graph characteristics vary non-linear and unstable (Tobnaghi et al., December,2013). V-I characteristics of solar cell sample at 15, 25, 30, 40, and 50 °C temperatures have been shown in Figure 1.

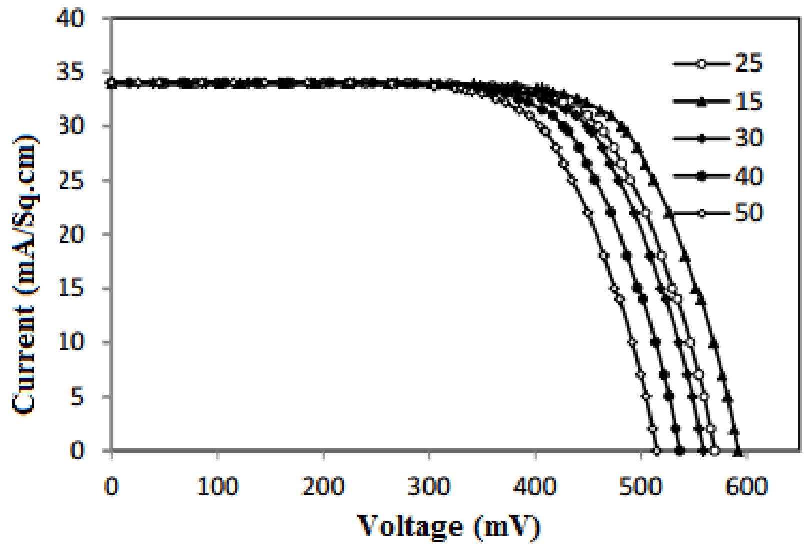

Figure 1: A Sketch of V-I Characteristics of a Solar Cell in different temperatures (Tobnaghi et al., December,2013)

It can be realized that V-I characteristics of solar cell vary under different temperatures. Escalations in temperature decrease the band gap of a solar cell, hence affecting the solar cell efficiency (Singh, 2008) (Singh & Ravindra, 2012)

Volt-Watt graph characteristics have a pronounced maximum generated power, the position of which varies considerably from the operating conditions, that is, resources, temperatures, radiance. When it changes operating temperature from +70 to -30 ° C, the voltage of the optimum operating point of the silicon solar battery increases approximately 1.5 times (voltage of a photocell varies within the range 0.5-0.75 V) (Shinakov et al., 2010). The current of a solar battery irrelevantly depends on the operating temperature. Theoretical analysis confirms that in comparison with parallel connection systems SB and AB (operating voltage of a SB, equals to the voltage of AB) energy effectiveness of the realization of the EPR of SB when deeply discharged AB may reach 50% (Shinakov et al., 2010).

3.2 Automatic tracking of the sun by the PV panels

The effect of the realization of the continuous mode of automatic tracking of PV panels for the sun is correspondingly significant. From preliminary investigations undertaken of energy efficiency of automatic tracking systems of PV panels for the sun proves that the effectiveness of the autonomous PV power plant in Mbabane Government Hospital (blood bank) compared to the horizontal arrangement of PV panels is as follows:

- If the solar battery exhibits an angle equal to the latitude of the location, the efficiency is 20%;
- When using single-axis tracking system the sun, the efficiency is 42%;
- The application of dual-axis tracking system of the sun, the efficiency is 51%.

On average for the different locations of off-grid photovoltaic power plants in Swaziland, i.e. Siteki Mzilikazi, Langa and Mbabane, the potential of increasing energy efficiency through the use of tracking systems for the sun rises by 31% for single-axis systems and 46% -for biaxial.

3.3 Impact of the re-design of solar cell structure

The likelihood of improving the design of solar battery structure with the view of increasing the exploitation of the energy efficiency factor results to the high sensitivity photocells elements to temperature. As the temperature increases the efficiency of PV batteries, like most other semiconductor devices is reduced. It is therefore necessary to take all measures to reduce the heat, inevitable under the scorching direct sunlight. Further complicating the situation is that the sensitive surface is rather fragile solar cells covered by the protective glass or transparent plastic. The result is a kind of "greenhouse" aggravating overheating.

Practically no information is available about the work on the investigation of the effectiveness of specific measures and devices that effect cooling of solar batteries of PV solar panels.

4. How the off-grid PV plant operates

The principal distinctiveness of the designed PV power plant is the;

- Simultaneous use of a stepper motor control method with automatic guidance of PV panels in the direction of the sun,
- EPR of SB and the establishment of an integrated management of power plant control system by dividing its operating period with periods interchanging task between EPR and stepper drives.

The employment of stepping techniques to ascertain maximum power is the most suitable for use in autonomous PV power plants (Hesari, 2016). The coordination of extreme regulator with the charger settings is achieved quite simply by a discrete adjustment feedback in the channel voltage of the solar battery. This method is widely used in photovoltaic power systems of automatic space vehicles (Shinyakov, 2007).

Extreme regulator of any type (analog-digital, digital, and micro-processor) hardly increases the weight of control apparatus, but instead has a low energy consumption and increases the efficiency of the solar battery to 98-100% (Shinyakov et al., 1997) (Shinyakov, 2007).

5. Spontaneous PV panel solar tracking operations

Figure 2 depicts a sketch of a mechanical system of vertical and horizontal rotations (azimuth and elevation) of solar PV panels.

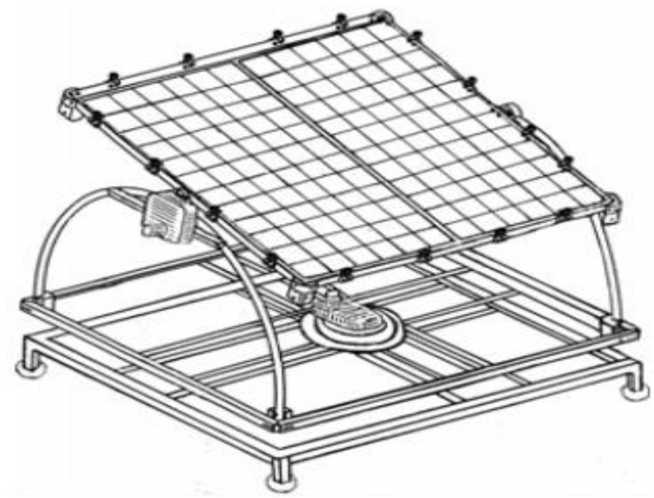

Figure 2: A sketch of the mechanical system of vertical and horizontal rotations of PV panels

The basic components of the mechanical system of a stand-alone PV power plant presented in Fig. 2 are: the frame with two PV modules GS-S-160 or KSM-180; the non-stationary frame; an immovable frame; rotation regulator in elevation; rotation regulator in azimuth; two stepper motor type SM-5D; two sun position sensors. The fixed immovable frame consists of welded steel frame of the four corners of the core and the tubular elements with four corner supports and one central support in which a rotating shaft is installed. The rotation of the shaft is provided by a stepper motor SD-5D through the worm gear and spur gear. Fixed securely to the lower support frame assembly, wherein rotation of the shaft is provided through the use as a central element of a spherical bearing, and the radial thrust bearings provide the smallest friction connection. The movable frame consists of welded steel frame with fixed thereon driven gear connected to a central shaft and a lower support unit keyed for rotation around the vertical axis installation. The same two arcs fixed frame in which the frame is installed with the axis of rotation KSM-160 modules through the collar and worm gear stepper motor SM-5D for the rotation in elevation. As a law of enforcement mechanisms, to ensure the rotation of the PV system, worm gears with a gear ratio of 1: 250 are used, which allows the use of stepper motors with rated torque load torque - 0.1 Nm. Worm gearboxes allow to exclude spontaneous change of the PV solar panels position relative to the sun under the influence of wind loads.

6. Designed off-grid PV plant operations

Fundamental and operational illustration of the off-grid PV power plant is shown in Figure 3.

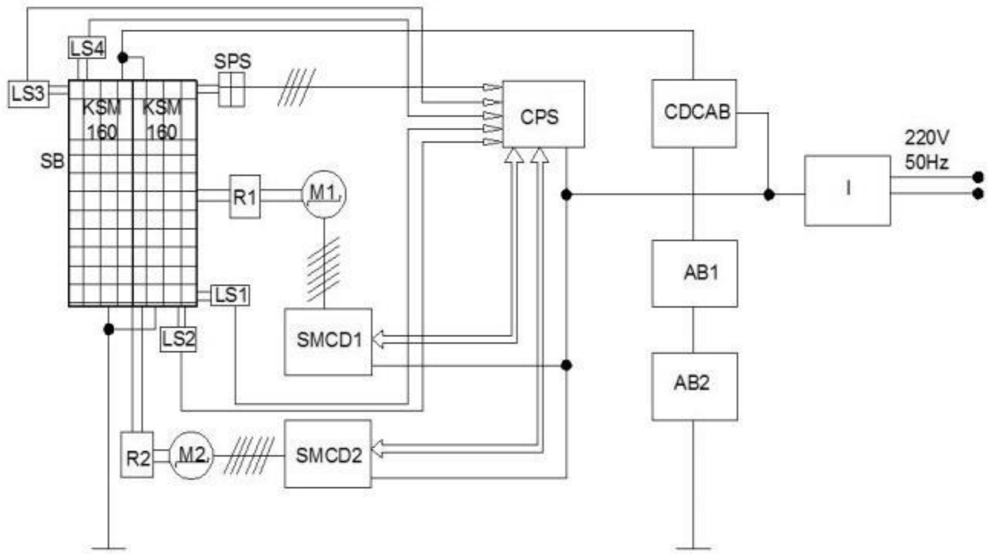

Figure 3: Structural and functional schematic diagram of an autonomous PV power plant

In Figure 3 the following symbols are designated as follows: SB is the solar battery; CDCAB - control charge/discharge of AB; I is the inverter; AB1 and AB2 accumulator batteries (storage devices); M1and M2 are stepper motors; R1, R2 are reducers; SMCD1, SMCD2 are stepper motor control drivers; SPS is the sun position sensor; CPS is the control pointer at the sun and LS1 to LS4 are limit switches. This autonomous PV plant system uses an inverter with sinusoidal output TS 1500-224, connected to two series accumulating or storage batteries, type TUDOR T12V 155FT and two solar PV panels of the type KSM 160. In addition, the developed regulator that points at the sun consist of the microcontroller (MC) STM32-F103, the DC-DC Converter, five operational amplifiers, IC, provides connectivity to RS 485 with an external computer through the Converter (I - 7561).

The tracking system for automatic step control, consists of two sensor positions of the sun, the guidance control on the sun, the two stepper motors with gearboxes, two power drivers, stepper motors, and four limit switches, provides two-coordinate mechanical movement of the solar battery, horizontally - not less than 180 degrees and vertically - not less than 70 degrees.

Using the sun position sensor, controller guidance and stepper motor driver provides the PV plant system with rotations about the axis of rotation discretely 1-5 degrees per movement cycle, thus reducing the energy costs of movement when tracking the sun. In the event there is no guidance provided by the stepper motors, no energy is consumed. To reduce jerks and swings by moving the controller for controlling stepper motors using positioning mode, i.e. it is the restriction on the speed and acceleration when moving from one location to another. Limitations of critical rotation angles in both planes is provided by the limit switches (LS1 – LS4), mounted on the immovable frame of the PV plant system and the control pointer at the sun. The controller (CDCAB) uses the charger circuit based on the voltage stepdown converter (SDC), as displayed in Figure 4. The circuit is designed to guarantee the minimum conditions of the power loss. In the study, it is determined that optimal frequency conversion 50 kHz, selected power field transistor IRFPS3810, have a low channel resistance.

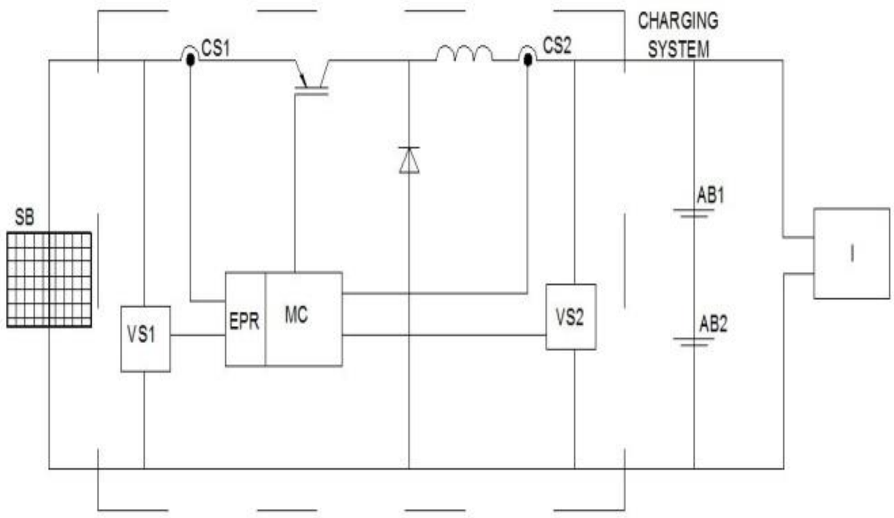

Figure 4: Functional sketch of autonomous PV power plant with recognition functions of EPR of SB

The charging system is controlled by a MC Atmega128, combining the functions of the user interface with the formation of the control action on power transistor (VT1). There are two modes of operation; the first one is the manual mode - a mode of stabilization of the solar battery voltage, where you can set the desired operating point on the constant voltage charge (CVC) of the SB. Second, is the automatic mode - EPR of the SB mode. In this mode, the search for the operating point of the CVC with maximum power output occurs. The operation algorithm feedback of this mode is demonstrated in Figure 5.

7. The feedback control algorithm process

Before switching on the charging system, the survey of the voltage sensors VS1 and VS2 occurs only in the occasion the open circuit voltage of the SB exceeds the voltage of AB, then the charger is switched on. Another condition is the inclusion of the not fully charged rechargeable battery, which is determined by the voltage AB, which shall not exceed a maximum value.

Afterward is a survey of the mode of operation of the memory, determining a desired feedback mode. In this mode, the sampled current sensor SB (CS1 multiple unit) and the voltage sensor SB (VS1), is considered as SB output. The obtained measured value of the input power P_{SB_NEW} is compared with the power value P_{SB_OLD} measured before the assignation of the control action. In the event P_{SB_NEW} is greater than $P_{SB\_OLD,}$ then the control impact sign ($\Delta\gamma$) does not change, which indicates the correct direction of movement of the operating point for the input voltage ($V_{IN)}$.

However, if there is a reduction of power, that is, P_{SB_NEW} is less than R_{SB_OLD}, then the operating point is moving down the V_{IN}, the sign changes, SB voltage is reversed $\Delta\gamma = - \Delta\gamma$. The property of the algorithm is the continuous movement of the operating point at V_{IN}, which is necessary for the detection of an ultimate

V_{IN} and search for a new value when a drift of V_{IN} happens. After the "capture" of the maximum power position of the operating point, the algorithm oscillates in the vicinity of the extreme values.

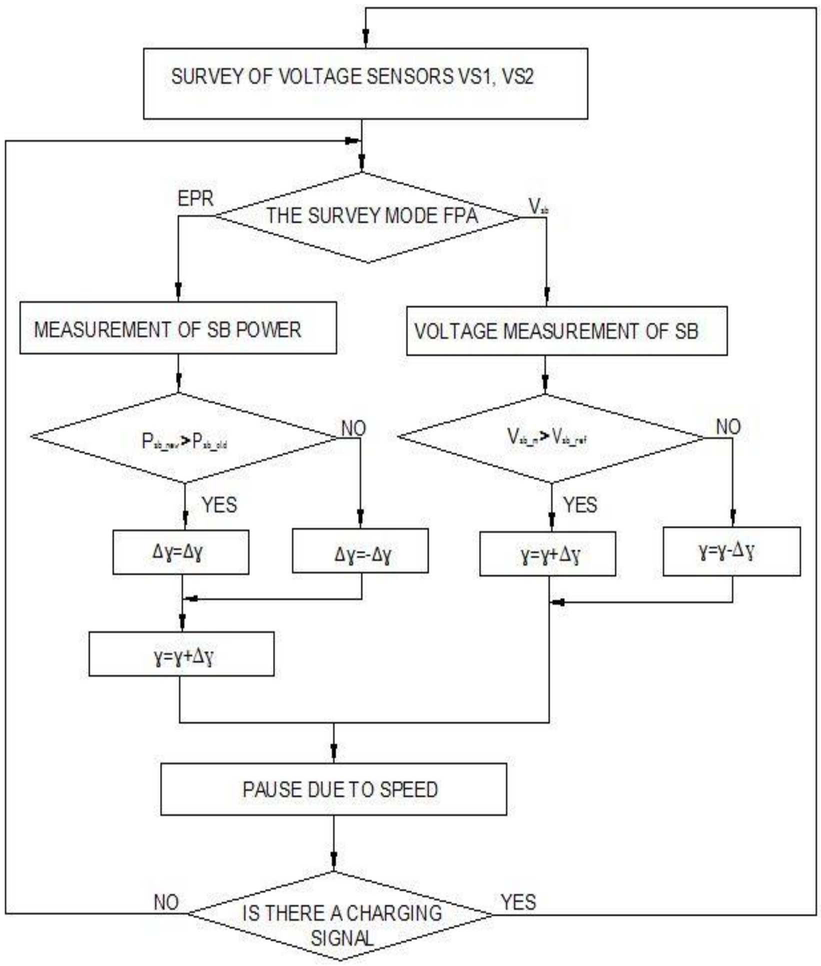

Figure 5: - Feedback Algorithm Process (FAP) ***(Shinyakov et al., 1997)***

In the algorithm there is a pause between the introduction of control action and survey, measurement sensors, which is necessary for the completion of transient processes caused by the operating action, and measure the steady-state value. It is obvious that the pause determines the frequency of control actions and, therefore, the search for the uttermost capacity, i.e. performance feedback. Therefore, a factor limiting the performance of the memory is the time of transients in the power converter, determined by inertial smoothing filters connected at its output.

8. Conclusion

There is presently no sufficient considerable field data and experimental results available that demonstrates the effectiveness and applicability of EPR and sun tracking of PV panels of off-grid PV power plants. Hence, this paper will assist in realizing the EPR technique and the automatic tracking of PV panels for the sun. The study validated that EPR and sun tracking of PV panels proves to be the most effective method of improving the energy efficiency of autonomous PV power plants.

The PV power plant which is fully autonomous will have a negligible loss of energy due to the provision of guidance mechanism on the sun, (energy costs can be determined at the stage of experimental studies) and optimized to not less than 30-50% energy efficiency.

Furthermore, this work is envisioned to serve as a foundation for additional feasibility and practicability studies into small and large scale application within the manufacturing sector where there is an escalating necessity to produce more off-grid, independent PV power plants.

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Biographies

Mr S. B. Dlamini received his Bachelor of Engineering and Technology in Mechanical Engineering from the People's Friendship University of Russia, Moscow in 2010. Since 2010, he has been actively involved in the consulting industry in areas such as the design of HVAC systems for residential and commercial buildings, renewable energy technologies and artificial intelligence. From 2015, he became a full time lecturer in Swaziland College of Technology (SCOT) in the department of Mechanical Engineering up until today. His research interests are in areas of photovoltaics (PV), renewable energy and energy efficiency technologies of buildings. He is currently working towards his MTech degree at the University of Johannesburg.

Mr E. Bakaya- Kyahurwa is a graduate of Mechanical Engineering from Makerere University (1986). He also studied at Kings College, University of London for his Msc in Mechanical Engineering (1990). Prior to joining academia Mr Bakaya-Kyahurwa held the position of Maintenance engineer at Ugma Engineering Corporation, a large metallurgical workshop in Uganda where he worked for several years.

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