Active Power Management of Islanded Interconnected Distributed Generation

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***Abstract*—The present paper proposes a management of active power in distributed generation considering an islanded mode. Power system is a complex system from the point of view of its constitution, operation and management. Because of energy sources scarcity and energy increasing demand in most of the electrical power systems worldwide, renewable energy exploitation continue to attract researches and exploitation of this weather depending resources. When considering the island mode or without connection to the main grid, of the distributed generation its operation and control became more difficult or uncertain based their dependencies on the weather. Using optimal theory, this paper solve the management of interconnected microgrids operating in islanded mode. Matlab software is used to solve all optimisation problems.**

***Index Terms*—Microgrid, active power, power system**

I. INTRODUCTION

Renewable energy resources (RER) demonstrated to be one of the most promising and useful energy model. In interconnected mode, more advantages can be cited: reliability and stability enhancement [1], [2]. When the connection of the renewable energy generation (REGEN) to the main grid is not made possible, or is not feasible, its operation and management are serious issues that can face a "stand alone renewable energy system". Based on the energy generated from the PV and wind farm, the system could not be meet the energy demand because on their variable nature. In most of the remote renewable energy system (RES), the battery energy system storage (BESS) and diesel generator (DGEN) support the operation and the management of the constituted system [1]. Both are uses to mitigate the issues of active power demand and active power generation fluctuations of weather depending energy generation resources as usual used in remote area power system applications.

The medium and low voltage networks are undergoing a lot of transformations because of the integration of power flow of energies coming from renewable sources or depending on the weather [3]. With an uncertain production and a variable demand power, the power flow becomes frequently reversed and difficult to handle or to manage. Some authors in the existing literature have proposed control and management models to solve this issue. Researchers in [4] have proposed a control strategies for multi microgrids (MGs) islanding operation by means of a smart transformers. In their research smart transformer was used within the context of multi MGs in order to enhance the possibility of islanding operation via the identification of new control functionalities. A fuzzy-based approach for MGs islanded operation was presented in [5]. Marei and Soliman [6] have proposed a coordinated voltage and frequency control of inverter based distributed generation (DG) and distributed ESS for autonomous MGs. One advantage of the proposed control system was its unified structure for the different operating modes. The research proposed a methodology for MG management in islanded conditions aiming to maximise the duration of power supply taking into account the availability of renewable sources and stored energy.

Researchers [7] have proposed a study on the operation optimisation of an isolated island MG with renewable energy layout planning. The proposed operation plan obtained the effect of a planned utilization rate of annual renewable energy of 40% or more. The authors [8] have implemented a multiple slack terminal direct current DGs for smooth transitions between grid-tied and islanded states. A counter was used to ensure bus voltages at both sides of contactor have been matched stably minimize inrush current. Stochastic energy management of MGs during unscheduled islanding period was proposed in [9]. According to this framework, the probability distribution of islanding duration needs to be estimated, instead of predicting its exact value. Bayhan and Rub [10] have proposed a simple control technique for DGs in grid connected and islanded modes. Each DG unit was controlled by the voltage control technique in islanded mode whereas the DGs controlled by feed forward based control technique in grid connected mode so as to ensure the seamless transition.

Researchers [11] have proposed regulation of voltage in islanded DGs using distributed constraint satisfaction. Several cases studies are simulated to evaluate the performance. Research [12] has proposed a local energy supply possibilities, with islanding DG case study. Based on the measurements and operational experience, a

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calculation method has been established to compare the traditional solution and the island operation possibilities. Control for grid connected and intentional islanded operation of distributed generation was presented in [13]. The paper has presented a control algorithm to detect grid supply failure and the intentional islanding operation of distributed generations. Energy and frequency hierarchical management system using information gap decision theory for islanded MGs was proposed in [14]. To address a robust hierarchical energy and frequency reserve management architecture, the problem was transmitted into a single-level mixed integer linear programming model and solved appropriately over 24-h scheduling time horizon. Athira and Ravikumar [15] have presented an energy management in islanded DC MG using fuzzy controller to improve performance. The research have developed and implemented a prototype model of the energy management system of DC MG in islanding mode.

The proposed model deals with two microgrids; the first is composed by a wind and photovoltaic generation and a battery energy storage system. The second microgrid is made by two engine generators. The configuration is completed with five loads. Three sections constituted the rest of this paper as follows: Section II highlights the modelling of the problem. Section III presents the proposed optimisation model and Section IV gives the data used and experimental results, finally Section V summarises the founding of this paper. The main contribution of this article is the proposition of the control-management model and experimental results obtained after simulations.

II. MODELLING OF THE PROBLEM

A. Proposed Model

The system of study is composed of two networks interconnected via one tie-line. Network 2 is essentially powered by two generators that operate on a well-established schedule. This is often the case of areas inaccessible to electrical energy via the natural network. If one of the generator works, the other is at rest and/or it can be used as the energy reserve in case of the active power demand increases (load demand). In order to reduce the operation cost related to the generators (Generator 1 and Generator 2), the interconnection with a microgrid 2, composed by a PV and wind generating systems with the battery energy storage, to relieve the functioning of Microgrid 1. When the diesel generators in Microgrid 1 working in their limits, Microgrid 2 brings an active power via a tie-line, that have as objective to relieve the operation of the two diesel generators and to allow a good loads management of the interconnected system (electrical network). The rated power of the two engines generator are fixed, the active power from wind farm and photovoltaic generations are given and used under profile forms.

B. Mathematical Model

The proposed system given in Fig. 1, described two areas or microgrids. Microgrid 2 is constituted by a PV arrays ($P_S(k)$), wind farm ($P_W(k)$), an energy storage system ($P_B^+(k)$ discharging mode) and ($P_B^-(k)$ charging mode) and two loads: one critical ($P_{L2}(k)$) and one no critical ($P_{L2}(k)$). Microgrid 1 is made up with a two diesel generators ($P_{E1}(k)$ and $P_{E2}(k)$), two critical loads ($P_{L3}(k)$ and $P_{L4}(k)$) and one normal load ($P_{L5}(k)$). The power flow giving the stability of the proposed system is given as follows:

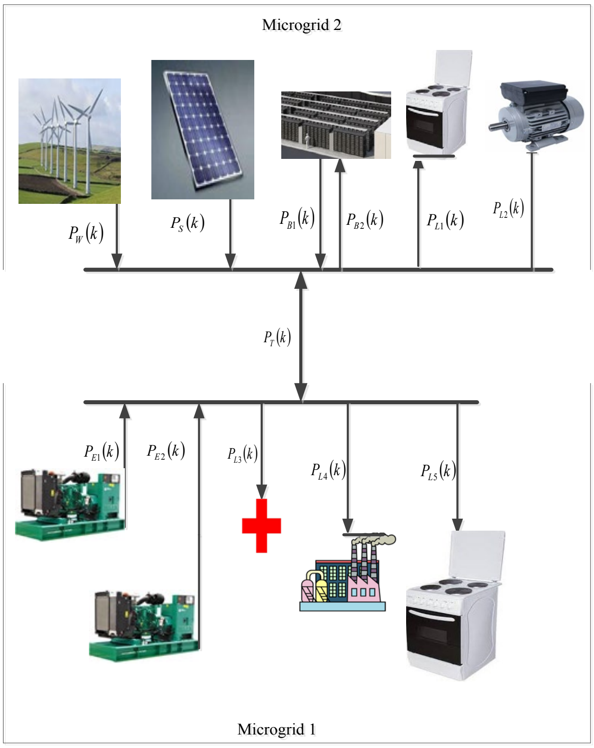

Fig. 1. Interconnected microgrid systems

From Microgrid 2

$$P_W(k)+P_S(k)+P_B^+(k) \geq P_B^-(k)+P_{L1}(k)+P_{L2}(k) \quad (1)$$

From Microgrid 1

$$P_{E1}(k)+P_{E2}(k) \geq P_{L3}(k)+P_{L4}(k)+P_{L5}(k) \quad (2)$$

From these Equations we can deduct:

- The total load:

$$P_{LT}(k) = P_{L1}(k)+P_{L2}(k)+P_{L3}(k)+P_{L4}(k)+P_{L5}(k) \quad (3)$$

- Total active power generated:

$$P_{GT}(k)=P_W(k)+P_S(k)+P_B^+(k)+P_{E1}(k)+P_{E2}(k) \quad (4)$$

- The following constraints are considered for the proposed system:

$$P_{E1}(k)=P_{E2}(k)=20 \text{ MW} \quad (5)$$

According to the constituted system, the following information should be taken into account:

$P_{L3}(k)$ Critical load high level (alimented 24 hours);
$P_{L4}(k)$ Critical load average level 1 (alimented 24 hours when power is available);
$P_{L2}(k)$ Critical load average level 2 (alimented 24 hours when power is available)

$P_{L1}(k)$ No-critical load
$P_{L5}(k)$ No-critical load

The active power flowing in the tie-line is determined as follows:

$$\Delta P_{TL} = P_S\left(\int \Delta\omega_1 dt - \int \Delta\omega_2 dt\right) \qquad (6)$$

where ΔP_{TL}, P_S, $\Delta\omega_1$, $\Delta\omega_2$ are respectively the power flow variation between Microgrid 1 and Microgrid 2; the synchronizing power and the frequency difference for Microgrid 1 and Microgrid 2.

C. *Objective Functions*

The objective function to be considered for this model is given in three parts:

1) Maximisation of the renewable energy production;

$$J_1 = \left[-\max \sum_{k=1}^{N}\left(P_W(k) + P_S(k)\right)\right] \qquad (7)$$

2) Minimisation of the diesel consumption;

$$\begin{cases} J_2 = \left[\min \sum \left(aP_{E1}^2(k) + bP_{E1}(k) + c\right)\right] \\ + \left[\min \sum \left(aP_{E2}^2(k) + bP_{E2}(k) + c\right)\right] \end{cases} \qquad (8)$$

3) Active power demand control;

$$J_3 = \left[\min \times \Delta t \times \left(P_T(k)\right) + Bf \times \Delta t\right] \qquad (9)$$

The multi-objective function is defined as follows:

$$J = w_1 J_1 + w_2 J_2 + w_3 J_3 \qquad (10)$$

where a, b and c are parameters from the manufacturer, w_i are the weight factors, $Bf\times\Delta t$ parameter depending to the frequency deviation.

III. PROPOSED ALGORITHM

To solve the proposed model and take into account the nonlinearity characterisics, the power system Fmincon solver in Matlab was used. The optimisation model is given as follows [1]-[3], [16], [17]:

$$\min f^T x \qquad (11)$$

Subject to the following constraints

$$\begin{cases} A \times X \le B \\ A_{eq} \times A = B_{eq} \\ L_b \le X \le U_b \end{cases} \qquad (12)$$

where $L_b \le X \le U_b$ is the variables bounds; $AX \le B$ is the inequality constraint of the proposed system; $A_{\text{eq}}X = B_{\text{eq}}$ is the battery dynamics equality constraint.

The power flow characterising the studied system from different elements is represented by X, which is a binary integer vector. All the optimal process is related to this variable and it is given under vector representation as follows:

$$X = \left[x_1, x_2, \ldots\ldots, x_N\right]^T \qquad (13)$$

Nine steps were used when solving the problem with Fmincon as follows:

1. Variables definitions
2. Formulations of matrices giving the linear inequality;
3. Determination of the equality constraints matrices;
4. Lower and upper bounds formulations;
5. State of charge matrix formulation;
6. Starting point serching;
7. Evaluation process using the objective function and the set of constraints.
8. Iterations and decision process
9. End process and results collection.

The battery energy storage system is characterised by its state of charge (giving the battery dynamic), for the proposed model, the SOC of the storage system is represented as follows in (14), for the purpose of it control, using the linear equality constraint:

$$\begin{cases} SOC(0) - h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k) - P_{B1}^{-}(k)\right) \le SOC^{\max}\right] \\ SOC^{\min} \le SOC(0) - h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k) - P_{B1}^{-}(k)\right)\right] \end{cases} \qquad (14)$$

where h is a coefficient taking into account the charging and discharging of the battery.

IV. EXPERIMENTAL ANALYSIS OF THE PROPOSED MODEL

A. *System Data*

Engines Diesel 1 and Diesel 2 constituted the main energy generator sources (E1 and E2) having the following rating power $P_{E1}(k)=P_{E2}(k)=20$ MW, rated frequency is 50 Hz. The characteristics of PV arrays ($P_S(k)$) and wind farm ($P_W(k)$) and a group of loads are given and used under profile form. PV arrays, wind farm in Microgrid 1 and Microgrid 2, and for the loads are used as profile form. Optimal control using Fmincon was implemented in Matlab 2010a with a processor Genuine Intel (R) CPUT2250 Duo 1.73GHz and a RAM of 1 GB. For the two engine generators the following coefficients (data) used are [2], [3], [16], [19]-[21]:

$$a = 0.00435, \quad b = -0.002675, \quad c = 1.41195 \qquad (15)$$

B. *Result and Discussion*

The results from this model is summarizes in the following figures. Fig. 2 and Fig. 3 show the maximum active power output and the available active power from PV and wind generation system, respectively. Fig. 4 and Fig. 5 show the active power variation from the battery energy storage system (BESS) and its state of charge (SOC), respectively. Active power deviations in the tie-line are show in Fig. 6 and Fig. 7. The frequency deviations of the interconnected system monitored on the tie-line are show in Fig. 8 and Fig. 9.

The exam of Fig. 2 and Fig. 3 shows a high production of active power from the renewable energy at the following time: from 1h00 to 3h00; 5h00 to 6h00 and from 8h0 to 00h00. A good average of active power generation can be seen from 8h00 to 00h00 which is ±36 MW Three times have characterized the loads supply according to their importance, Table I summarizes the three times or scenarios. The supplementary active power from the BESS, stored when the system was operating in normal or balance condition, is used to compensate power deficit of interconnected system while the it going under disturbance condition (due to the load variations from one area).

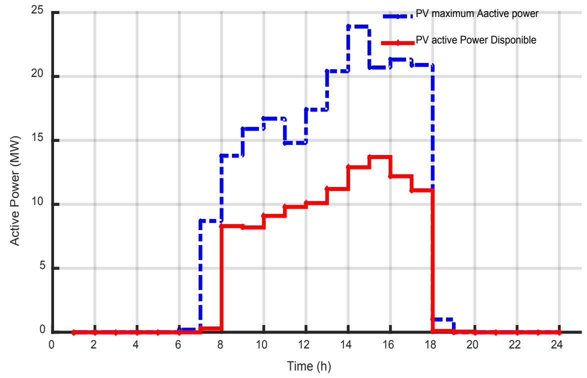

Fig. 2. Active power from photovoltaic generation systems

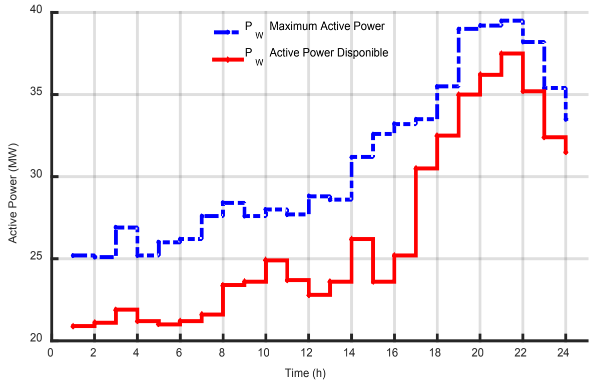

Fig. 3. Active power from wind generation systems

TABLE I. LOADS MANAGEMENT OF THE INTERCONNECTED SYSTEM (IN %)

$P_{Li}(k)/h$	1h to 7h	8h to 13h	14h to 00h
$P_{L3}(k)$	100	100	100
$P_{L4}(k)$	100	100	80
$P_{L2}(k)$	100	100	80
$P_{L1}(k)$	80	80	100
$P_{L5}(k)$	80	80	100

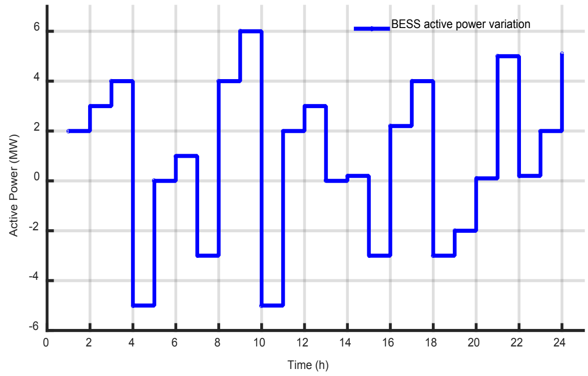

Fig. 4. Active power from battery

Charging (when the BESS taking power from the MG) and discharging (when the BESS supply the MG) as showed in Fig. 4, gives it dynamic (Fig. 5). This figure show how the BESS was working during the simulation process. Two limit values or constraints were set up for the BESS dynamic: SOC min and SOC max. The variations were comprised between (0.3 to 0.9%).

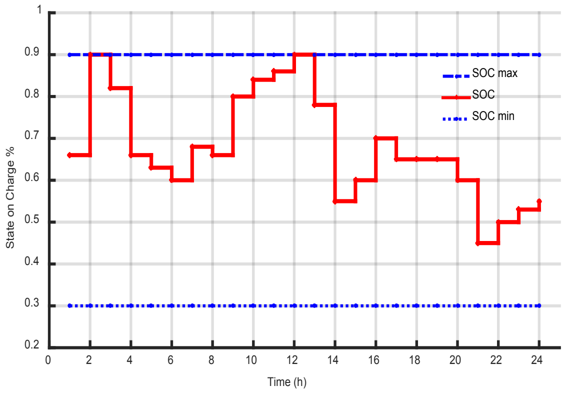

Fig. 5. SOC of the battery during 24Hours

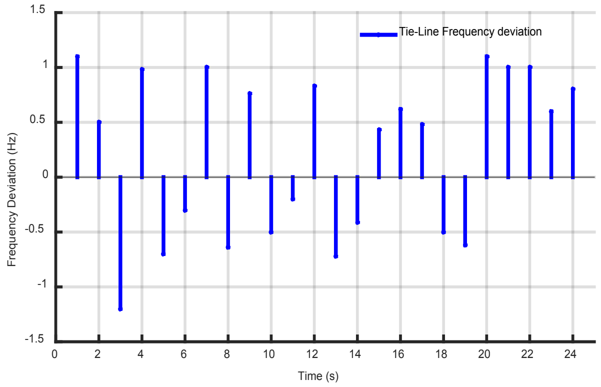

Fig. 6. Frequency deviation in the tie-line

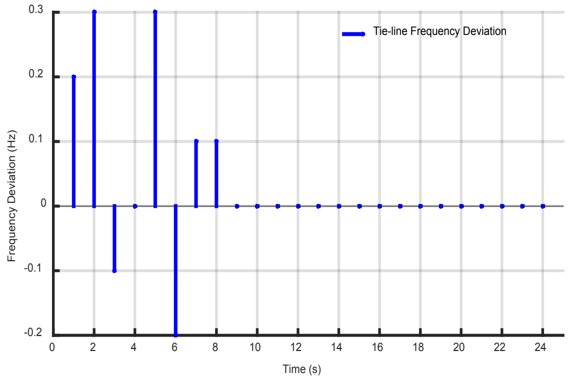

Fig. 7. Frequency deviation on the tie-line

When the MG is working under disturbances, active power and frequency deviation occurs. This mean when these deviations are not controlled, power quality and system reliability become low and the MG may go under load schedding or unexpected blackout may occurs. To avoid these scenarios (load schedding and blackout) the active control and load management of the proposed system working in islanded modes should be achieve with a good active power demand (load) schedule. Based on the proposed model after simulation results show in

Fig. 6 and Fig. 7 the frequency deviation in the tie-line, this mean the active power from MG 1 going to MG 2 and from MG 2 to MG 1 without any control strategy.

This situation is dangerous beacause the load management is not applied to regulate the load frequency and to keep the stability of the interconnected system. Based on the proposed control and management approach strategy, Fig. 7 show the output the results obtained after simulation. The load frequency variations in the tie-line were controlled during 24 seconds, simutation time. The performance of the proposed controller can be seen, this mean the way the frequency variations goes to decreasing until reaching zero from 7th second.

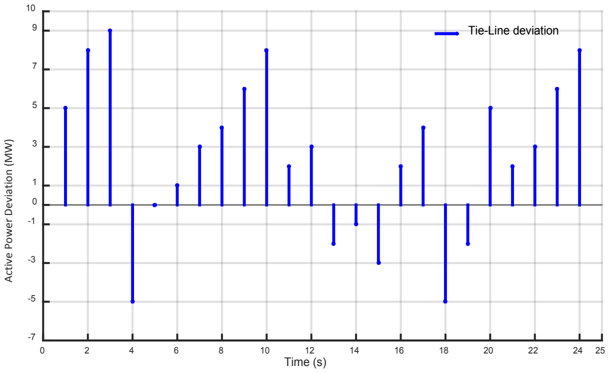

Fig. 8 Active power deviation in the tie-line

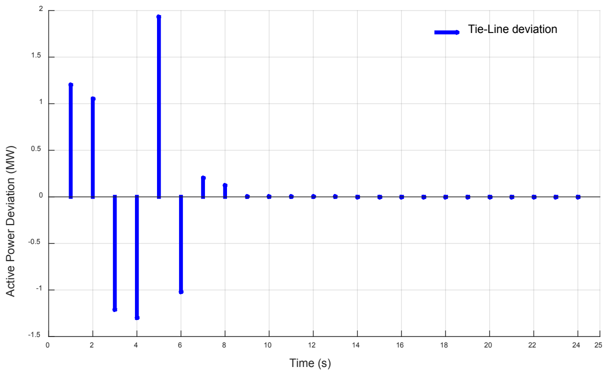

Fig. 9. Active power deviation on the tie-line

The active power transfer between the two interconnected microgrids without any control system during 24 seconds simulation time, is given in Fig. 8, while the Fig. 9 gives the simulation output of the proposed controller. The exam of the simulation results given in Figs. 8 and 9 show the differences between the controllled and no-controlled interconnected system. When controlling the active power deviations in MG 1 and MG 2 through the flow of power in the tie-line, the same scenarios can be seen when comparing with the frequency control given in Figs. 6 and 7. For instance, the ripples giving the variations of the active power in Fig. 9 are degreasing starting from the 7th and 8th second, from 9th second it ca be seen a constant attenuation of the wave of frequency variation until the end of the simulation period. The overshoot and the settling times when considering Fig. 9 are considerably reduced.

V. SUMMARY

The study proposed dealt with the management of active power considering an islanded interconnected of distributed generation. The scarcity and the increasing demand of energy nowadays remains the main reason of exploitation of renewable energy resources because of its availability and easy transformation. When considering the island mode or without connection to the main grid, of the distributed generation its operation and control became more difficult or uncertain based on their dependencies on the weather. Their control in this situation should be handling with care to avoid unplanned load shedding or a blackout. From the proposed research simulation shown that the operating cost of the two diesel generators has decreased significantly due to the contribution of the active power from the renewable energy sources, this can see from the proposed simulation results. The proposed model reduced consirably the overshoot and the settling times, this can be seen from the simulation results.

From the obtained simulations results, it can be concluded that the proposed method has show the effectiveness while controlling the active power in distributed generations working in islanded mode.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Y. Sun group leader conducted the research; D. H. Tungadio formulated the problem; mathematical modelling and wrote the Matlab M-File code for optimisation; analyzed the data and did the simulations; result collection and wrote the paper; all authors had approved the final version.

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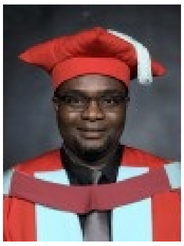

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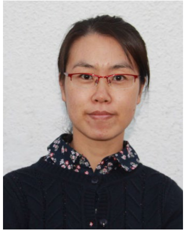

Yanxia Sun received her joint qualification: DTech in Electrical Engineering, Tshwane University of Technology, South Africa and Ph.D. in computer science, University Paris-EST, France in 2012. She has therefore an approach that brings together computing and electrical engineering. She has more than 10 years teaching and research experience. Currently she is serving as an Associate Professor University of Johannesburg, South Africa.

Dear Prof. Sun,

$$\begin{cases} SOC(0)-h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k)-P_{B1}^{-}(k)\right)\leq SOC^{\max}\right] \\ SOC^{\min}\leq SOC(0)-h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k)-P_{B1}^{-}(k)\right)\right] \end{cases} \tag{14}$$

I still have a queation on Eq. (14).

From the form of (14), it is a set of equations which consists of two quations: the first is

$$\mathrm{SOC}(0)-k\left[\sum_{t=1}^{j}\left(P_{B1}^{+}(k)\right)-\left(P_{B1}^{-}(k)\right)\leq \mathrm{SOC}^{\max}\right] \tag{14a}$$

and the second is

$$\mathrm{SOC}^{\min}\leq \mathrm{SOC}(0)-k\left[\sum_{t=1}^{j}\left(P_{B1}^{+}(k)\right)-\left(P_{B1}^{-}(k)\right)\right] \tag{14b}$$

Obviously, (14b) is an inequation, but the (14a) is neither an equation nor an inequation!

Please give a reasonable explanation.

Do you think Eq. (14) might be the form as below?

$$\begin{cases} \mathrm{SOC}(0)-k\left[\sum_{t=1}^{j}\left(P_{B1}^{+}(k)\right)-\left(P_{B1}^{-}(k)\right)\right]\leq \mathrm{SOC}^{\max} \\ \mathrm{SOC}^{\min}\leq \mathrm{SOC}(0)-k\left[\sum_{t=1}^{j}\left(P_{B1}^{+}(k)\right)-\left(P_{B1}^{-}(k)\right)\right] \end{cases} \tag{14}$$

However, Dr. Diambomba H. Tungadio insists the right form is

$$\begin{cases} SOC(0)-h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k)-P_{B1}^{-}(k)\right)\leq SOC^{\max}\right] \\ SOC^{\min}\leq SOC(0)-h\left[\sum_{k=1}^{j}\left(P_{B1}^{+}(k)-P_{B1}^{-}(k)\right)\right] \end{cases} \tag{14}$$

Please give your full explanation here.