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Black Start Application in Power System Restoration using Distributed Energy Resources

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ABSTRACT

The threats to the power systems being caused by extreme weather-related events are increasingly alarming. Safeguarding the Power System against all forms of instability requires adopting new and integrated approach. The integration of the distributed energy resources (DERs) into the Power grid especially at the distribution level has greatly changed the dynamics of the modern power system. Improving the resilience of the power grid by the application of DERs in black start application is explored in this study. The black start restoration is formulated as a dynamic optimisation problem and the restoration sequence capable of improving the grid resilience is developed. The implementation is carried out on the Nigerian 48-bus system and the simulated results demonstrate the DERs ability in contributing significantly to power system black start.

Keywords: distributed energy resources, power system restoration, black start, dynamic optimisation, grid resilience, extreme weather events.

NONMENCLATURE

Abbreviations	
DGs	*Distributed Generators*
BSR	Black Start Restoration
RCSs	Remote Controllable Switches
ESS	Energy Storage Systems
DERs	Distributed Energy Resources
KCL	Kirchhoff's Circuit Law

1. INTRODUCTION

With the increasing effects of climate change culminating to frequent occurrence of extreme weather events, the power system is exposed to increased vulnerability. Reinforcing the power system to improve its resilience to such events becomes not only necessary but also a cost effective approach, when compared to the annual inflation adjusted cost of weather-related outages estimated to be between \$25 billion and \$70 billion according to [1]. This is besides the social, political and economic impacts of such occurrence which are often times unquantifiable.

As the cost of energy from renewable sources continues to be seemingly competitive with that of conventional sources, there appears to be a significant transformation in the application of renewable energy technologies. This is evidently witnessed in the massive deployment of DERs into the distribution network as either an alternative energy source or in conjunction with existing conventional sources. For instance, DERs are increasingly being deployed in power system restoration during blackout events to support critical infrastructures and facilities.

The potential of DERs application in black start services for power system restoration is continuously being investigated and some of the approaches adopted is being reviewed in this section. [2] reported the progress made in the deployment of electric buses in the distribution system to facilitate and enhance the system resilience using heuristic method aimed at obtaining the allocation plan by solving a mixed-integer linear program. The validation of their proposed method was by the use of numerical simulations performed on the IEEE 123-node feeder system. [3] proposed a look-ahead service restoration method based on distributed generators (DGs) to serve critical loads in a secondary network distribution system. Their assumption was based on the availability of a hierarchical control infrastructure, DGs and load which can be centrally controlled.

A two-stage heuristic method was developed and applied in addressing the critical load restoration problem by modelling a critical load problem as a chance-constrained stochastic program [4]. By first creating a strategy table, the linear integer optimization problem was solved to obtain the restoration strategy. Their restoration sequence appeared interesting but their approach was yet to be practically implemented.

Similarly, a three-stage service restoration approach which involved first establishing a feasible restoration tree from microgrid to critical loads, then incorporating the reserve capacity as constraints of the restoration problem and lastly using emergency power supply vehicles, was proposed by [5]. Using this method, numerical simulations were conducted to demonstrate the effectiveness of the approach while the evaluation of the system resilience was achieved by the application of non-parametric kernel density estimation.

In view of the significantly increasing contributions of DERs in the provision of alternative energy at the LV distribution level as well as in other power systems applications whether on grid or off grid, its roles in black start restoration cannot be over emphasized. As noted in [6 - 8], recent technological research have shown the potential of employing DERs along with remote controllable switches (RCSs) in the provision of black start services.

Given the prevalence of blackout incidences around the world within the last decade and particularly within the African continent as observed by [9, 10], this paper presents a black start strategy which integrates a combination of DERs in the provision of power system restoration. While the proposed method has a universal application, it is however adopted in this study to provide a localized solution to Nigeria's recurrent blackout challenges. The black start restoration is formulated mathematically as a dynamic optimisation problem and implemented sequentially to aid in power system restoration thus improving the grid resilience. Analysis of the proposed method is carried out for different time intervals during the day taking into account the energy availability from PVs and energy storage systems (ESS). Although DERs integration into the grid is a fast growing and trending area of research, however, it's application in black start applications is novel. Moreso, to the best of the researcher's knowledge, there's no existing literature in the Nigerian context that has addressed this specific area, hence the quest to fill this knowledge gap.

The rest of the paper is organised as follows: section II presents the mathematical formulation and discusses the test system. Section III briefly examines the model test system used for the implementation. The results and discussion is presented in section IV. In section V, the conclusion of this work and future research direction is captured.

2. MATHEMATICAL FORMULATION

2.1 Objective Function of the BSR

The formulation of the black start restoration problem is achieved mathematically as a dynamic optimisation problem with the objective usually defined to maximise the total restored energy during the considered time-frame [11].

Objective function of the BSR can be formulated as:

$$\text{Max } \sum_{t\epsilon J} f\left(p^{L}_{l,t}, p^{\emptyset}_{g,t}, Q^{\emptyset}_{g,t}, x^{BR}_{ij,t}, x^{L}_{l,t}, \Delta t\right), \quad (1)$$

where $t \in \mathcal{T} \coloneqq \{1,2, \dots, T\}$ is adopted to represents the set of steps. The horizon length is T. $\boldsymbol{P}^{L}_{l,t}$ is considered to be a vector representing the three-phase load demand on node l at step t. The set of all the buses such as load buses and DG buses is represented as $\mathcal{N} \coloneqq \{1,2, \dots, N_n\}$, while the set of buses connected to the loads is captured as $l \in \mathcal{L} \subseteq \mathcal{N}$. The three-phase active and reactive power respectively generated by a DG on node g at time step t is given as the vectors $\boldsymbol{P}^{\emptyset}_{g,t}, \boldsymbol{Q}^{\emptyset}_{g,t}$. For the set of substation buses as well as the buses connected to dispatchable DGs, their representation is given as $g \in \mathcal{G} \subseteq \mathcal{N}$. The switching state of a switchable line between node i and j respectively, at time step t is expressed as ($x^{BR}_{ij,t}$). The energization level of a load at node l is $x^{L}_{l,t}$ at step t while Δt is the length of time between two successive steps. $f(\blacklozenge)$ is used to represent the function which indicates the restored load (e.g., in kW) as a result of the control variables. Equation (1) represents the total amount of load restored at all the considered steps.

In equation (2) the optimization function is formulated and used in implementing the simulation.

$$\text{Max } \sum_{l\epsilon\mathcal{L}} \sum_{t\epsilon J} \sum_{\phi\epsilon\{a,b,c\}} \beta^{L}_{l} . p^{\emptyset}_{l,t} . \Delta t \quad (2)$$

$$\beta^{L}_{l} . p^{\emptyset}_{l,t} . \Delta t + 0 p^{\emptyset}_{g,t} + 0 Q^{\emptyset}_{g,t} + 0 x^{BR}_{ij,t} + 0 x^{L}_{l,t} \quad (3)$$

The node voltage magnitude and the line power is obtained by solving the power flow equation. [12] using Kirchhoff's circuit law (KCL), formulated the general form of power flow model for distribution system. Making reference to this, the power flow model taking into consideration the energisation status of each line at each time step is formulated along with the power balance constraints for each bus at each step. Hence, the formulation of equations (4 to7):

2.2 Inequality constraints

$$0 p^{L}_{l,t} + 0 p^{\emptyset}_{g,t} + 0 Q^{\emptyset}_{g,t} - M e^{\emptyset}_{ij} x^{BR}_{ij,t} + 0 x^{L}_{l,t} \leq -\left\{\left(U_{i,t} - U_{j,t}\right) + M e^{\emptyset}_{ij} + \tilde{Z}_{ij} S^{*}_{ij} + \tilde{Z}^{*}_{ij} S_{ij}\right\} \quad (4)$$

$$0 p^{L}_{l,t} + 0 p^{\emptyset}_{g,t} + 0 Q^{\emptyset}_{g,t} + M e^{\emptyset}_{ij} x^{BR}_{ij,t} + 0 x^{L}_{l,t} \leq \left(U_{i,t} - U_{j,t}\right) - \left(\tilde{Z}_{ij} S^{*}_{ij} + \tilde{Z}^{*}_{ij} S_{ij} - M e^{\emptyset}_{ij}\right) \quad (5)$$

2.3 Equality Constraints

$$\sum_{l:l=i,l\in\mathcal{L}} p^{L}_{l,t} - \sum_{g:g=i,g\in\mathcal{G}} p^{\emptyset}_{g,t} + 0 Q^{\emptyset}_{g,t} + 0 x^{BR}_{ij,t} + 0\, x^{L}_{l,t} = \sum_{h:(h,i)\in B} p^{BR}_{hi,t} - \sum_{j:(i,j)\in B} p^{BR}_{ij,t} \quad (6)$$

$$0 p^{L}_{l,t} + 0 p^{\emptyset}_{g,t} - \sum_{g:g=i,g\in\mathcal{G}} Q^{\emptyset}_{g,t} + 0 x^{BR}_{ij,t} + 0 x^{L}_{l,t} = \sum_{l:l=i,l\in\mathcal{L}} Q^{L}_{l,t} - \sum_{h:(h,i)\in B} Q^{BR}_{hi,t} + \sum_{j:(i,j)\in B} Q^{BR}_{ij,t} \quad (7)$$

where $\boldsymbol{e}_{\boldsymbol{ij}}^{\emptyset} \in \mathbb{Z}_2^3$ is the vector with binary entries to represent the phases. If a single-phase line is assumed for branch $(i,\ j)$ (e.g., B-phase), then $\boldsymbol{e}_{\boldsymbol{ij}}^{\emptyset} = [0,1,0]^T$.

The vector of the three-phase apparent power flowing from bus i to j through line $(i,\ j)$ at step t is $\boldsymbol{S}_{ij,t} = \boldsymbol{P}_{ij,t}^{BR} + \boldsymbol{Q}_{ij,t}^{BR}$. The three-phase load demand on node i at step t is$(\boldsymbol{P}_{l,t}^{L} + \boldsymbol{Q}_{l,t}^{L})$. Equations (4) and (5) ensures that the constraints are applied only to energised lines with an exception to transformers and voltage regulators. They selection of the value for M is done such that the constraints are only valid when the line is energised.

2.4 Connectivity Constraints for Loads

The formulation of the connectivity constraints for loads is achieved taking into consideration certain conditions proposed by [13]. These includes the following:

1. The restoration of loads can only be accomplished upon the energisation of the terminal buses.
2. At the energization of the terminal bus, the immediate restoration of switchable loads occurs.
3. Upon load restoration, it shouldn't be shed.

The formulation of these constraints is presented thus:

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + 0x_{ij,t}^{BR} + x_{l,t}^{L} \leq s_{l,t}^{N} \quad (8)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + 0x_{ij,t}^{BR} + x_{l,t}^{L} = s_{l,t}^{N} \quad (9)$$

Equation (8) is implemented to ensure that a switchable load should only be energised when it's connected to an energised node. For non-switchable load, equation (9) is formulated to ensure that its gets energized immediately it's connects to an energised node.

2.5 Connectivity Constraints for Lines

Just like the connectivity constraints for loads, a similar rule was adopted in the formulation of the connectivity constraints for lines. In summary, the connectivity constraints for lines can be expressed as [13]:

1. One of the terminal buses must be energised in order for a switchable line to be closed.
2. Once a non-switchable line is closed, a terminal bus is immediately energised.
3. When being energised, a line cannot be tripped.

The mathematical formulation of the constraints is represented in equations (10) to (14):

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq s_{i,t}^{N} \quad (10)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq s_{j,t}^{N} \quad (11)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} - x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq -x_{ij,t-1}^{BR} \quad (12)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} = s_{i,t}^{N} \quad (13)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} = s_{j,t}^{N} \quad (14)$$

The formulation of Equations (10) and (11) are to ensure that both end nodes of a switchable line are energised if a switchable line is energized while equations (13) and (14) guarantees that non-switchable lines are energised immediately once one of the end nodes is energised.

2.6 Topological Constraints

The operation of most distribution system are implemented using radial topology. The topological constraints is formulated taking into consideration a series of rules which ensures the feasibility of a BSR sequence. These rules are based on the inter-temporal relationship among binary decision variables and is defined for lines and nodes. Hence, according to [13], the topological constraints can be expressed using the following rules:

1. The energisation of a bus block not connected to any black-start DG or substation can be achieved by anyone of the lines connected to this bus.
2. At time step t, a bus block energised, and de-energised at step t – 1, must be energised by at least one switchable line at step t.
3. The energisation of each switchable line is possible only if at least one of its end buses is energised at the former interval.
4. The line cannot be closed if both end buses of a switchable line are energised. This would avoid loop formation.

The mathematically representation of these rules is expressed by the following constraints:

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} - \sum_{ij} x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq \sum_{ki} x_{ki,t}^{BR} \quad (15)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} - \sum_{ij} x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq -\sum_{ij} x_{ij,t-1}^{BR} - \sum_{ij}\left(x_{ki,t-1}^{BR} - x_{ki,t-1}^{BR}\right) + 1 + Ms_{i,t-1}^{N} \quad (16)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq s_{i,t-1}^{N} + s_{j,t-1}^{N} \quad (17)$$

$$0p_{l,t}^{L} + 0p_{g,t}^{\emptyset} + 0Q_{g,t}^{\emptyset} + x_{ij,t}^{BR} + 0x_{l,t}^{L} \leq \left(s_{i,t}^{N} - s_{i,t-1}^{N}\right) + \left(s_{j,t}^{N} - s_{j,t-1}^{N}\right) - x_{ij,t-1}^{BR} \quad (18)$$

3. Model Test System

The model of the Nigerian 48-bus system adopted for the implementation of the proposed BSR method and assessment of its performance is shown in Fig. 1.

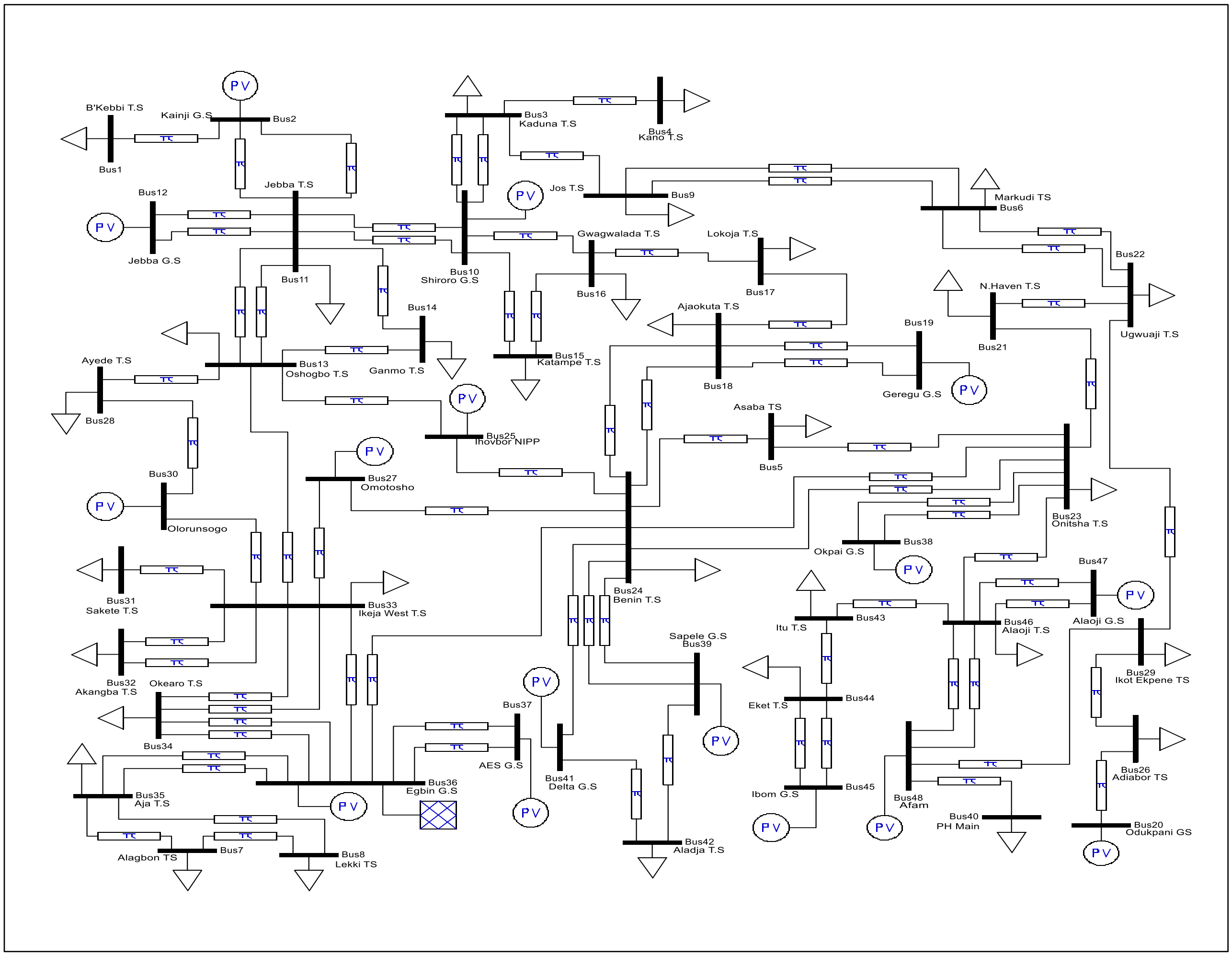

Fig. 1 Model of Nigerian 48-bus System

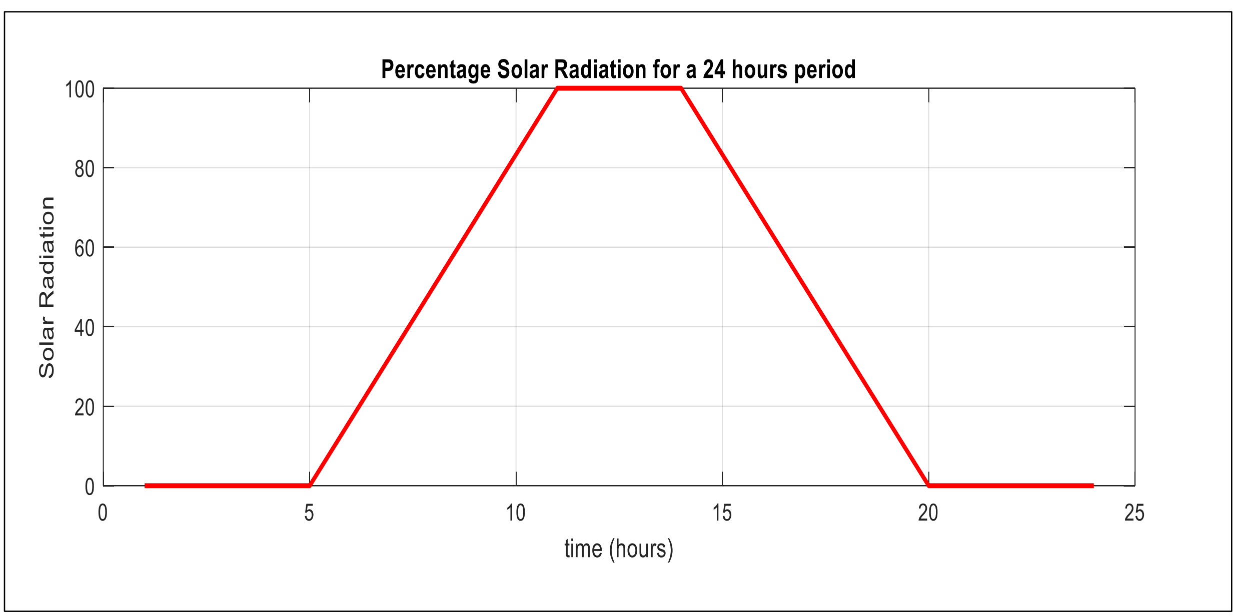

Fig. 2 Average Daily Solar Radiation Availability

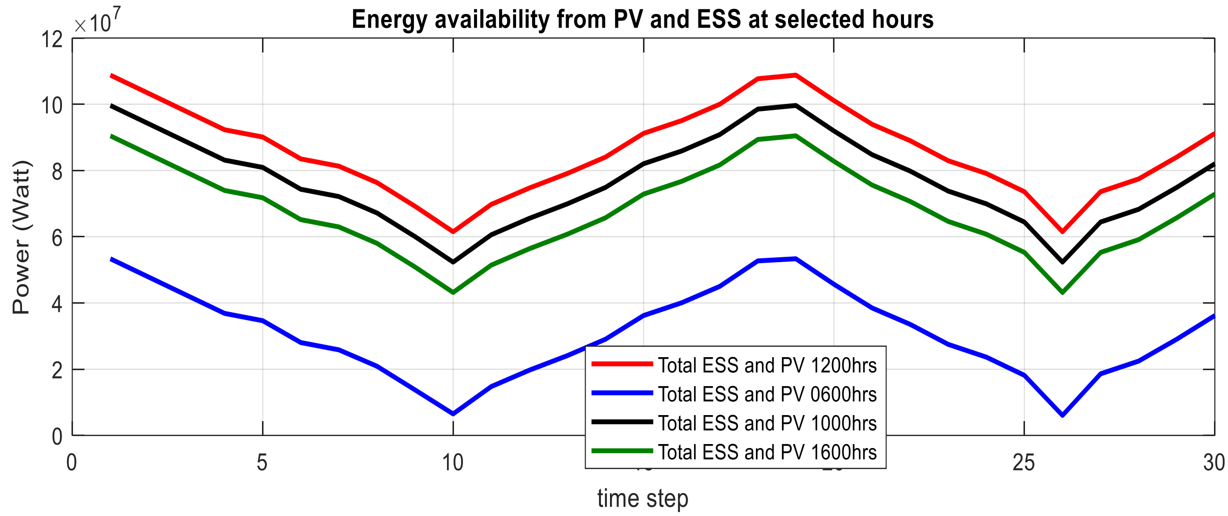

Fig. 3 Combined ESS and PV Energy Availability at Selected Hours

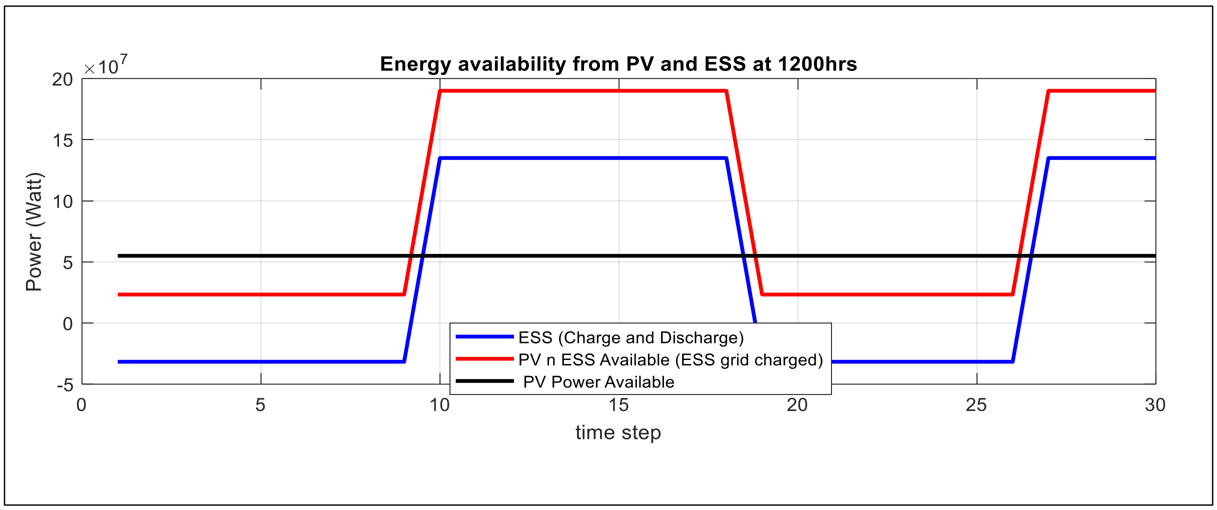

Fig. 4 ESS Charge and Discharge Sequence

4. Results and Discussion

The contributions of both the ESS and PVs to BSR is assessed and discussed in this section. Fig. 2 shows the percentage of solar radiation availability within a 24 hours period. From the plot, it can be seen that 100% PV availability is only achieved between the hours of 11am and 2pm while 50% PV availability is obtained between the hours of 8am & 11am and 2pm & 5pm respectively. Between the hours of 6am & 8am and 5pm& 7pm respectively, only 20% of solar availability may be achieved. In terms of total PV solar availability, this accounts for 12% of a hundred percent availability, 25% of fifty percent availability and 17% of twenty percent availability respectively. In Fig. 3, the energy availability from both ESS and PV is shown. The ESS is being charged both from the grid supply and the PV energy. The total energy availability and values at four different hours of the day is being examined and used in simulating the proposed BSR scenario. High PV penetration especially during the peak solar radiation period significantly supports the proposed system restoration depending on the time the proposed blackout events occurred and the duration. The characteristics of the energy storage system is presented in Fig.4. The charging sequence of the ESS for the chosen time step is shown. Regardless of the rate of charge and discharge, it can be seen that the PV power available is fairly constant. This scenario remains true only during the active solar radiation period of the day as illustrated in the plot.

5. Conclusions

The increasing integration and participation of DERs in the power balance of today's power system has provided new possibilities as well as grid flexibility. One of such possibilities is the application of DERs in power system black start restoration which this paper analysed. The BSR was formulated as a dynamic optimisation problem. Using the Nigerian 48-bus system, the implementation was carried out and the level of participation of energy storage systems (ESS) and PVs in the BSR evaluated. The performance analysis of the participating DERs is carried out for different time intervals during the day taking into account the energy availability from PVs and ESS. The simulation results indicates the ability of the DERs to significantly contribute to power system restoration.

The model response to load restoration, particularly the ESS and PV contributions to cold load pickup as well as the various switching states of lines, buses and loads is the focus of the next phase of our research.

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