On Battery Storage System for Load Pickup in Power System Restoration

Nemica Kadel, *Student Member*, *IEEE*, Wei Sun, *Member*, *IEEE*, and Qun Zhou, *Member*, *IEEE*

Abstract— **During power system restoration, it is critical to maintain system frequency stable to avoid any further outage or cascading events. Load pickup is one of the most important tasks to keep generation-load balance for a stable system frequency. In current industry practice, small loads are suggested to be picked up incrementally to avoid any instable frequency dip. However, slow load pickup may prolong the system restoration process. As the fast response energy resources, battery storage system (BSS) can expedite the load pickup by compensating the imbalance between generation and load. In this paper, a battery dispatching strategy is developed for faster and more reliable load pickup in system restoration. The frequency response rates (FRRs) of generators are utilized to pick up loads in each step while maintaining frequency stability. Batteries are used to maximize the load pickup. The State of Charge (SOC) of batteries is monitored and kept within specified limits. Simulation results demonstrate that batteries can support to increase total served energy and reduce system restoration time. The battery charging/discharging time and sequence depends on the generation and load profile, and the size of BSS. This paper further discusses the impact of FRR of BSS on frequency dynamics in load pickup.**

Index Terms—**Battery Storage System, Frequency Response Rate, Load Pickup, Power System Restoration, State of Charge.**

I. INTRODUCTION

Power system restoration is critical to bring the system back to normal operating conditions following an outage or blackout. Generally, the restoration process can be divided to three stages, preparation, system restoration, and load restoration [1]. Blackstart (BS) generating units initiate the restoration process by providing the cranking power to start non-blackstart (NBS) generators. As generators start to ramp up, load must be picked up to balance the system frequency and voltage profile [2]. Frequency deviation caused by load pickup in each restoration stage is a major concern for system operators. Therefore, loads need to be restored in small blocks to avoid the violation of prime movers' constraints [3]. Generally, hydro (HY), combustion turbine (CT), and steam turbine (ST) units can only pick up the load with 15%, 25% and 5% of each unit's capacity, respectively [4]. These numbers represent the maximum load each generator can pick up with an acceptable frequency dip due to the sudden change of load, defined as frequency response rates (FRRs). PJM uses these FRRs to maintain the frequency within 60±0.5Hz [5].

There are several efforts to address the frequency issue in system restoration. An analytical model was developed in [4] to calculate the FRR of different prime movers to the sudden change of load. In [6], the authors used FRRs to determine the best sequence of load pickup in an interconnected system of hydro and steam units. It was recommended to pick up load first by HY units then ST units to maintain the maximum frequency dip within limits. A wide area measurement system was applied in [7] to determine a suitable amount of load to pick up or generation to increase by predicting the progression of frequency stability. Considering different issues related to load pickup, an average system frequency model was developed in [8] to determine the amount of load that can be safely picked up at a substation.

To overcome the deficiency or surplus of generation during load pickup, battery storage system (BSS) can be used to compensate the imbalance and expedite the load pickup process. Currently, batteries are used to establish the communication system or serve critical load in the early stage of system restoration [9]. FERC order 784 [10] is designed to promote the utilization of batteries as fast response storage units for frequency regulation. It also opens the opportunity to use high capacity BSS to accelerate the restoration process. The largest tested battery system is a 34MW NaS battery system installed in Rokkasho village, Aomori, Japan. AES has installed a 12MW Li-ion battery system for frequency regulation [11]. Therefore, the utility-scale BSS can serve as either load or generation in the restoration process.

In this paper, a battery dispatching strategy is developed for faster and more reliable load pickup in power system restoration. By considering the FRR of different types of generators and state of charge (SOC) constraints of batteries, the charging/discharging sequence and time has been determined for BSS. Simulation results demonstrate that batteries can support to expedite the load pickup process. The battery dispatching strategy depends on the generation mix and the size of BSS. The proposed approach in this paper focuses on the steady-state analysis. The discussion of considering the frequency response rate of BSS has also been provided for dynamic analysis. The organization of this paper is as follows. Problem formulation and solution methodology are presented in Section II. Case studies and simulation results are discussed in Section III. Section IV presents a discussion of the dynamic analysis approach. Conclusions are summarized in Section V.

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II. PROBLEM FORMULATION

During different stages of system restoration, batteries can be used as either load or generation. Initially, batteries can be operated in the discharging mode as BS units to crank NBS units or pick up critical load. When generators begin to ramp up, loads need to be picked up to maintain system frequency. If there is more generation than the maximum amount of load that can be restored, batteries can be operated in the charging mode. If there is no enough generation to restore load, rather than waiting for the generation ramping up, batteries can be operated in the discharging mode as a power source. This process will continue until the whole system is restored back to normal operating conditions. The problem formulation is shown as follows.

A. Objective Function

The objective is to maximize the total restored energy during the restoration period. As shown in Fig. 2 in [11], the total restored energy E_{load} is the unshaded area under the load pickup curve, as given by:

$$E_{load} = \sum_{i\in\Omega_L} \left[\left(T - t_{istart} \right) \times P_{Li} \right] \tag{1}$$

where, T is the given restoration period, t_{istart} is the pickup time of load i, P_{Li} is the MW of load i, and Ω_L=1,…,N_L is the set of all load. To maximize (1) is equivalent to:

$$Min \quad \sum_{i\in\Omega_L} \left(t_{istart} \times P_{Li} \right) \tag{2}$$

B. Constraints

Power balance: Generation and load should be equal all the time. Battery will be operated as either generation or load depended on the imbalance between available generation and load. This constraint can be formulated as:

$$\sum_{i\in\Omega_G} P_{Gi}\left(t\right) = \sum_{j\in\Omega_L} u_{jt} P_{Lj} \pm \sum_{k\in\Omega_B} P_{Bk}\left(t\right), \quad \forall t \in \Omega_T \tag{3}$$

where, $P_{Gi}(t)$ is the MW output of generator i at time t, $P_{Bk}(t)$ is the MW input/output of battery k at time t, u_{jt} is the status of load j at time t. When $t \geq t_{jstart}$, load j has been picked up and u_{jt}=1; otherwise, u_{jt}=0. Ω_G=1,…,N_G is the set of all generators, Ω_B=1,…,N_B is the set of all batteries, Ω_T=1,…,T is the set of time.

Generator output function: The generation output function is decided by the starting time, cranking time to ramp up and parallel with system, ramping rate, and generation capacity. In this paper, it is assumed that the generator start-up sequence has been determined using the method developed by authors in [13].

Generator frequency response rate: In [4], Adibi, et al., have developed FRRs for typical prime movers (CT, ST & HY) that are used in the initial phase of power system restoration. It has been simulated for a % range of generators' loads L and for % range of sudden load pickups ΔL. It has been shown that the prime movers' frequency dip ΔF is: (a) independent of the generators' loading L, but depends on their types and sizes (capacities); (b) proportional to the size of the sudden load pickup ΔL. These two attributes develop the FRRs ΔF/ΔL that is a constant number (index) for a given type of prime movers to be used in determining the allowable sudden load pickup and to determine the effective reserve distribution. In this paper, for 0.5Hz maximum frequency dip, FRRs of CT, ST, and HY units are 12%, 5%, and 13%, respectively. Then at each time of picking up load, the total amount of restored load should be smaller or equal to the summation of maximum allowable load pickup for all generators, as given by:

$$\sum_{j\in\Omega_L} u_{jt_{kstart}} \left(1 - u_{jt_{kstart}-1} \right) P_{Lj} \leq \sum_{i\in\Omega_G} \left(\mathrm{FRR}_i \times P_{Capi} \right), \quad \forall k \in \Omega_L \tag{4}$$

where, P_{Capi} is the generation capacity of generator i. In (4), only load to be picked up at time t_{kstart} will be included.

State of Charge of batteries: In order to operate batteries at high efficiency and also maintain the cycle life of batteries, battery SOC should be within certain limits, as given by:

$$SOC_{\min} \leq SOC_i\left(t\right) \leq SOC_{\max}, \quad \forall i \in \Omega_B \tag{5}$$

where, SOC_{min} and SOC_{max} are the lower and upper limits of SOC. In this paper, SOC of all units are maintained between 20% and 80% [14]. The relationship between functions of SOC and the battery output can be achieved as follows.

$$SOC_i\left(t\right) = \begin{cases} SOC_i\left(t-1\right) + \eta_c \times P_{Bi}\left(t-1\right)\Delta t, & \text{charging} \\ SOC_i\left(t-1\right) - \left(1/\eta_d\right) \times P_{Bi}\left(t-1\right)\Delta t, & \text{discharging} \end{cases} \tag{6}$$

where, η_c and η_d are the charging and discharging efficiency.

C. Search Algorithm

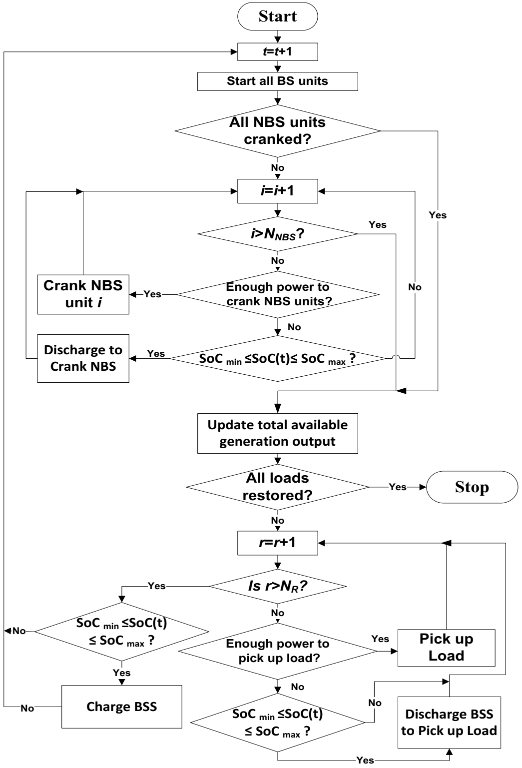

Figure 1. Flow chart of search algorithm.

The flow chart of proposed rule-based search algorithm is presented in Fig. 1. There are two stages of battery application in system restoration: crank NBS units and pick up load. As shown in the upper part of the flow chart, if there is surplus generation, batteries will be charged to store the energy; otherwise, batteries will be discharged to provide the cranking power to start NBS units. In the lower part, if there is no enough generation, battery will be discharged to pick up load; otherwise, batteries will be charged to store the energy. The SOC constraint of batteries will be always checked. The process will continue until all loads are restored.

III. SIMULATION RESULTS

Three case studies have been performed for illustration of the proposed model and solution methodology. Two BS units and one NBS units are used to pick up loads. The generator characteristics are shown in Table I [15]. Different load profiles are used in three cases to match the generation capacity. Based on the 6.78MWh battery used in power utilities for frequency regulation, different sizes of batteries are assumed in each case to compare the benefit of batteries in load restoration. Load pickup actions are performed every 10 minutes (1 p.u. time), and it is assumed that batteries have 100% efficiency in a fully charged state in the beginning.

TABLE I. GENERATOR CHARACTERISTICS

Unit	Type	MW Cap.(MW)	Ramp Rate (MW/hr)	Start-up Req.(MW)
Chester_4-6	CT	39	120	N/A
Conowingo_1-11	Hydro	385	384	N/A
Schuykill_1	Steam	135	135	2.7

A. *Case I - One BS Unit*

One BS unit (CT) is used to serve 11 loads, and each load is 3MW with equal priority. The ramp rate of CT is 20MW/p.u., and in each step, the maximum load that CT can pick up is 4.68MW using 12% FRR. Therefore, the surplus generation can charge batteries. Considering the SOC constraints, the charging/discharging schedule of battery will be determined. Three scenarios are analyzed, no battery, one 100kWh battery, and one 450kWh battery. The comparison of load pickup curves is shown in Fig. 2.

In the case of no battery, 3MW load is picked up at each step, and the load pickup curve is shown as the blue curve. When using one 100kWh battery, the load pickup curve is shown as the red curve. At each p.u. time, the surplus power between generation and load is 1.68 MW, and the total surplus energy in that time duration (10 minutes) is 280kWh. This is larger than the battery energy capacity of 100kWh. Therefore, this battery cannot be charged hence will not contribute to the load pickup. When using one 450kWh battery, the battery can contribute to the load pickup, shown as the green curve. The restoration time is decreased and total restored energy is increased. The SOC of this 450kWh battery is shown in Fig. 3. Based on this case study, it is found that the contribution of battery in load pickup depends on the size of the battery, generator ramp rate and FRR, load size, and the time duration between restoration actions.

B. *Case II - One BS Unit and One NBS Unit*

One BS unit (CT), one NBS unit (ST), and one 2.7MWh battery are used to serve part of the load profile in [11]. After starting up BS unit, CT provides 2.7 MW to crank NBS units. Considering 12% FRR of CT and 5% FRR of ST, the maximum load that two units together can pick up is 11.43MW. Two scenarios are analyzed, no battery, and one 2.7MWh battery. The comparison of load pickup curves is shown in Fig. 4.

In the case of no battery, the load is picked up according to their priority level, shown as the blue curve. When using the 2.7MWh battery, the battery can support to decrease total restoration time and increase total restored energy, shown as the red curve. The SOC of 2.7MWh battery is shown in Fig. 5. It can be observed that during the first five time intervals, the battery is operated in the discharging mode to pick up more load than the case without battery, and the SOC is reduced to the lower limit of 20%.

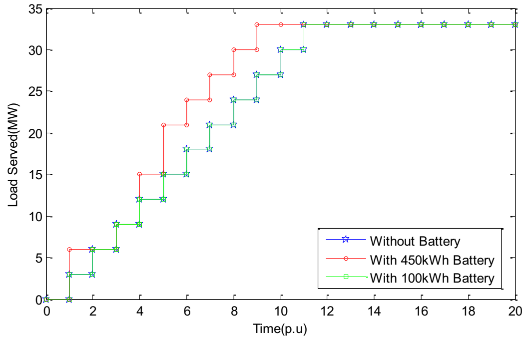

Figure 2. Comparison of load pickup under different scenarios.

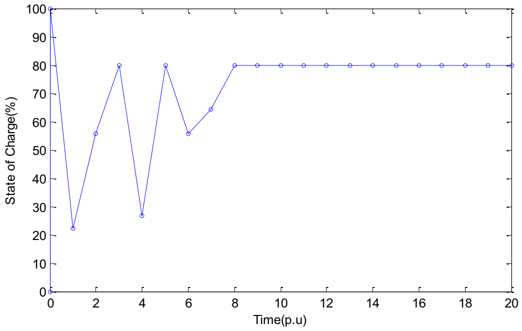

Figure 3. SOC of the 450kWh battery.

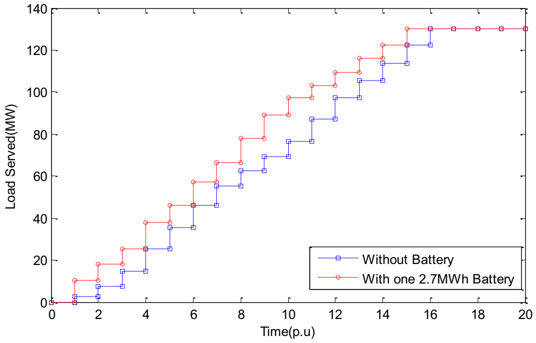

Figure 4. Comparison of load pickup under different scenarios.

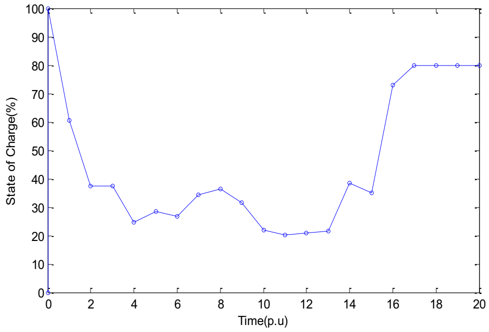

Figure 5. SOC of the 2.7MWh battery.

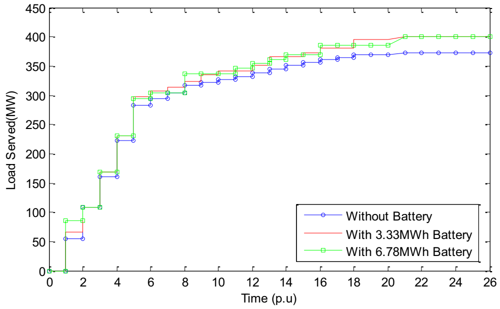

Figure 6. Comparison of load pickup under different scenarios.

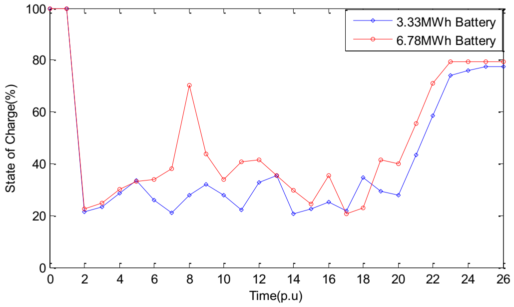

Figure 7. SOC of the 3.33MWh and 6.8MWh battery.

C. Case III - Two BS Units and One NBS Unit

Two BS units (CT and HY), one NBS unit (ST), and two different batteries of 3.33MWh and 6.78MWh are used to serve the load. The load profile in [12] is doubled to match the total generation capability. After starting up BS unit, CT and hydro units provide 2.7 MW to crank NBS units. Considering 12% FRR of CT, 13% FRR of HY, and 5% FRR of ST, the maximum load that three units together can pick up is 61.48MW. Three scenarios are analyzed, no battery, one 3.33MWh battery, and one 6.78MWh battery. The comparison of load pickup curves is shown in Fig. 6.

In the case of no battery, the load is picked up according to their priority level, shown as the blue curve. Different from previous two cases, some loads cannot be restored due to the deficiency of available generation to pick up the smallest size of remaining load, during the time period t_{22}-t_{25}. The total restored load is 375.6MW. If use 3.33MWh or 6.78MWh battery, the total 400.6MW load can be restored, shown as the red and green curves, respectively. Comparing these two scenarios, more load can be picked up in the early stage using 6.78MWh battery, which brings more total restored energy. The SOC of batteries in two scenarios are shown in Fig. 7. It can be observed that more energy can be restored and then used to pick up more load using 6.78MWh battery.

The summary of different scenarios in three cases is shown in Table II. It can be observed that batteries can support expedite the load restoration process. In Case 1, smaller size battery doesn't contribute to load restoration. In Case 2, battery can support to reduce restoration time and increase total restored energy. In Case 3, larger size battery can contribute to restoring more energy, but the restoration time doesn't change. Therefore, the benefit of batteries in load restoration depends on the generation mix, load profile, and the size of battery. The charging/discharging time and sequence needs to be carefully decided to maximize the benefit of batteries in system restoration.

TABLE II. Comparison of load restoration with and without batteries

Cases		**Total Restoration Time (pu)**	**Total Restored Energy (MWpu)**
Case 1	Without Battery	11	297.0
	With 100kWh Battery	11	297.0
	With 450kWh Battery	9	336.0
Case 2	Without Battery	16	1441.9
	With 2.7MWh Battery	15	1627.4
Case 3	Without Battery	21	5955.6
	With 3.33MWh Battery	19	6248.9
	With 6.78MWh Battery	19	6264.2

IV. DISCUSSION

In the proposed problem formulation, it is assumed that batteries can respond to control signal without any delay. Practically, batteries are connected through the control and management system to the grid. It is important to consider the dynamic performance of BSS. In the context of batteries' application in load pickup, the FRR of BSS will greatly impact the maximum load that can be picked up without violating the frequency limit. In the absence of battery dynamics associated with converters, inverters and transformer equipment, several reasonable ΔF/ΔL have been assumed in this discussion.

The test system has three types of generating units, CT, ST and HY. Generator parameters can be referred in [4]. The FRRs of three types of prime movers are calculated in [4]. Different FRRs are assumed for BSS. The characteristics of generators and battery are shown in Table III. In Case 1, there is no battery, as the base case. In Case 2, one 27MW battery with 40% FRR is added to the system. In Case 3, the FRR of battery is assumed to be 100%, which is approaching to the isochronal operation. In Case 4, battery is assumed to pick as much load as its capacity.

TABLE III. GENERATOR AND BATTERY CHARATERISTICS

Type		**No. of Unit**	**Unit Rate (MW)**	**Response Rate (%/Hz)**	**Response Rate (MW/Hz)**
ST		2	135	-12.6	-34.0
CT		3	16	-21.7	-13.9
HY		4	32	-29.4	-28.2
Battery	Case 1	N/A	N/A	N/A	N/A
	Case 2	1	27	-40.0	-10.8
	Case 3	1	27	-100.0	-27.0
	Case 4	1	27	N/A	N/A

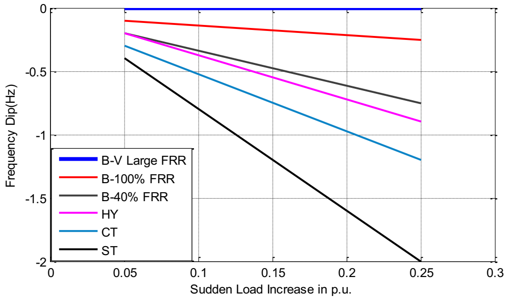

Figure 8. FRRs of ST, CT, HY, and three batteries.

A load increase of 50 MW happens to the system, and there is no adjustment in the governor's speed change position. The calculation of different FRRs of three batteries is shown as follows.

Battery I: $\Delta F / \Delta L = -2.50$ Hz / p.u. $\Delta L / \Delta F = -40$ % / Hz (-40)

Battery II: $\Delta F / \Delta L = -1.00$ Hz/p.u. $\Delta L / \Delta F = -100$ % / Hz (-100)

Battery III: $\Delta F / \Delta L = -0.00$ Hz/p.u. $\Delta L / \Delta F =$ large % / Hz (V large)

The comparison of FRRs of ST, CT, HY, and three batteries is shown in Fig. 8. Each unit and battery response to the sudden change of 50MW load based on their FRRs. The results are shown in Table IV. System maximum frequency dip can be calculated in the following equation:

$$Max.\ Freq.\ Dip\ (Hz) = Total\ load\ (MW)/Total\ FRR\ (MW/Hz)$$

For example, in Case I, system FRR is 76.1 MW/Hz (=34+13.9+28.2), and Max. Freq. Dip is 0.66 Hz (=50/76.1).

TABLE IV. LOAD PICKUP AND FREQUENCY DIP

Case	Load Pickup(MW)				Max Freq. Dip (Hz)
	ST	CT	HY	Battery	
I	22.34	9.13	18.53	0.00	0.66
II	19.55	7.99	16.22	6.21	0.58
III	16.49	7.74	13.68	13.10	0.49
IV	10.20	4.17	8.46	27.00	0.30

It can be observed that batteries can support to decrease maximum frequency dip. The higher battery FRR, the more benefit to system frequency stability. Batteries with high FRR can support to pick up more loads with the same amount of maximum frequency dip. Without considering battery FRR, system will pick up more loads, which may cause frequency instability. Therefore, the accurate value of battery FRR is critical to maximize the benefit of batteries and maintain system frequency in load pickup.

V. CONCLUSIONS

A battery dispatching strategy is developed for faster and more reliable load pickup in power system restoration. The frequency response rates of different types of generators are used to maximize the load pickup in each step and maintain frequency stability. The State of Charge of batteries is maintained within limits. Simulation results show that batteries can support to increase total restored energy and reduce load restoration time. The battery charging/discharging time and sequence depends on the generation and load profile, and the size of battery system. This work has demonstrated the great potential of using batteries to expedite the load pickup process in system restoration. In the future work, the dynamic behavior of battery system will be considered to calculate the accurate battery FRR. Also, the optimal battery management strategy in load restoration will be developed to facilitate system operators to achieve efficient system restoration plans.

VI. ACKNOWLEDGEMENTS

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VIII. BIOGRAPHY

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