## Optimization of Charge/Discharge Rates of Battery Using Two Stage Rate-Limit Control

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Optimization of Charge/Discharge Rates of a Battery Using a Two Stage Rate-Limit Control

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Abstract—Energy storage would play a critical role in the microgrids. In this paper, two stage variable rate-limit control for battery energy storage is proposed. The objective of this control scheme is to optimize the amount, rate and time-duration of the energy stored/discharged from the battery. Thus, the battery would charge/discharge at its optimized maximum rate in a hybrid energy storage system (HESS). Supercapacitor is used to form the hybrid energy storage system, to complement or supply the energy deficiency during the transient period. With the proposed control scheme, the stress levels on the battery is regulated by optimizing the charge/discharge rates of the battery. The advantages of the proposed control scheme also includes maintaining the state of charge (SOC) of the battery within the limits for longer duration. This control scheme is validated using real-time control hardware in loop (CHIL) using OPAL-RT and dSPACE.

Index Terms—Battery, Energy storage system, Hybrid energy storage system, Rate-limit control, State of charge, Supercapacitor.

I. INTRODUCTION

In microgrid, energy storage systems (ESS) are generally used to mitigate the power imbalances between the generation and the demand. Energy storage systems are also used to solve problems like energy management, peak shaving, power quality, load leveling, transient stability, voltage regulation and uninterrupted power supply. Besides the utilization in microgrids, ESSs are also getting popular in hybrid electric vehicles (HEV), more-electric aircraft, etc. These energy storage systems are characterized based on parameters like power and energy density, life cycle, ramp rate etc. [1]. Fig. 1 shows the energy and power density profiles of different energy storage units [2], [3].

Batteries and supercapacitors (SC) are most commonly used ESS technologies. In [4], [5], the authors proposed battery-based energy storage system to balance the intermittency of wind power. However, in battery-based energy storage system (BESS), power density and charge/discharge rates are not high enough to meet the peak/pulse load demand. If the batteries are subjected to support the highly fluctuating load demands, then batteries will be under high stress. This would be reflected as increase in charging/discharging cycles, ultimately leading to reduction in the battery life span [6]. However, batteries are typically used for supplying the power demand for longer duration, owing to its high energy density. Therefore, to stabilize the power fluctuations in the microgrid, capacitors with high power density have been proposed [7], [8]. But supercapacitor has low energy density, so it cannot support the load demand for long duration. The relative properties of the battery and the supercapacitor are shown in Table I. It shows that batteries have high energy density, but low power ramp rate (i.e. charging/discharging is slow relative to supercapacitor) [9]–[11]. On the other hand, supercapacitors have high power density and high power ramp rate (i.e. charging/discharging is fast relative to battery). But, none of the energy storage system has both the properties of high energy density and high power density. If only one type of energy storage system is used to meet all the requirements of power and energy capacities, then it will result in high installation cost. Therefore, in order to harness the advantages of both high energy and power densities, hybrid energy storage system (HESS) has been proposed to mitigate the issues of load demand and power generation fluctuations in most real-life microgrid, and remote area power system applications [11], [12].

| TABLE I | BATTERY VERSUS SUPERCAPACITOR PERFORMANCE [10] |
|-----------------------------|-----------------------------|-----------------------------|
| Specific energy density    | Lead acid battery          | Supercapacitor              |
| Specific power density     | 10-100 (W/kg)              | 1-10 (W/kg)                |
| Cycle life                 | 1000                       | > 500000                    |
| Charge/discharge efficiency| 70-85 %                    | 85-98 %                     |
| Fast charge time           | 1-5 hr                     | 0.3-30 s                    |
| Discharge time             | 0.3-3 hr                   | 0.3-30 s                    |

Fig. 1. Ragone chart showing the power density and energy density of different storages [13].
The authors in [14] have shown different possible configurations of the battery-supercapacitor HESS to harness the advantages of both batteries and supercapacitors. In [15]–[21], the authors have discussed different control algorithms for HESS. Mendis et al. demonstrated the advantages of adding a supercapacitor to a battery for a wind power system. Authors in [16], have studied the cost and performance analysis of HESS, and shown that it reduces the battery cost and improves the overall system efficiency. Amine et al. presented that adding the supercapacitor to battery, reduces the current stresses in battery. For wind power system, analysis of battery life time extension was studied using supercapacitor, and reported in [18], [19]. To regulate and reduce the power discharge rate from the power source during highly fluctuating load demands, Zhang et al. suggested to install hybrid energy storage system. An adaptive rate-limit control for batteries has been proposed by Ding et al. [21], to protect the primary power source during sudden load transients. Ahmed Mohamed et al. in their paper [22], described about energy management algorithm for mitigation of pulse loads in microgrid. They have used nonlinear regression technique to obtain the mathematical models of the system and fuzzy logic approach to control the pulse loads. However, this algorithm did not consider the charge and discharge rate limitations of the battery and did not explain clearly the coordination between the battery and the supercapacitor for controlling the pulse loads.

Most of the hybrid energy storage system control algorithms [23]–[27] work based on the principal that, batteries have to support the average power demand, while supercapacitors have to support the transient power demand. To achieve this, the total power demand is decomposed into low frequency power component (average component) and high frequency power component (transient component). The low frequency power component is supplied by the battery and high frequency power component is supplied by the supercapacitor. But most of these control algorithms did not consider the charge/discharge rate limit control and charge/discharge pattern of the battery while decomposition. As a result, the charging/discharging rate limits may cross the maximum value allowed for the battery, which makes the battery to operate at its maximum rate limit, thereby increasing the stress levels on the battery, which in turn, undesirably decreases the life span of the battery. To regulate these charge/discharge rates of the battery, researchers adopted a linear rate limiter. The control algorithms having rate-limit function feature either have a constant rate limit, resulting in suboptimal solution, or have a complex design for optimal solution [21]. Furthermore, the charge/discharge power patterns (power trajectory) of the battery during the transient period affects the energy stored/discharged. This would depend on the proportional-integral (PI) control parameters ($K_p$ & $K_i$), because these parameters decides the output (i.e reference battery current or power or duty ratio) of the PI controller based on the error signal (which contains different frequency components). These power patterns determine the energy stored/discharged from the battery, which in turn determines the state of charge (SOC), which is explained in the subsequent section. To solve these problems, an adaptive variable two stage rate limit control scheme is proposed. The objective of the proposed control scheme is to

1. optimize the energy stored/discharged from battery during the transient period,
2. optimize the charging/discharging rates of the battery, and
3. optimize the time duration for which the battery charges/discharges at its optimized maximum rate.

This control scheme has the advantage that it can protect the battery from abrupt charge/discharge within the constraints of available storage capacity. Therefore, in this paper an optimized solution for charge/discharge rates for the battery is proposed by introducing a variable two stage rate-limit control to reduce the stress levels, while regulating the energy stored/discharged by the battery.

The remainder of the paper is organized as follows. In section II, discharge/charge effects on battery is discussed. In section III, a general analysis of the HESS is presented. The proposed optimized solution is discussed in section IV. Experimental results are described in section V, followed by conclusions in section VI.

II. EFFECTS OF CHARGE/DISCHARGE RATES ON BATTERY LIFE

This section describes about how the charging and discharging rates effects the battery life. Experience shows that it is not simple to identify the battery life failure for the following three reasons [28], [29]:

1. Batteries are complex systems and having many operational interactions. Therefore, the reason of failure depends on a number of environmental and construction factors.
2. Batteries are long lived and testing to failure is a long and costly process.
3. Accelerated testing of complex systems often prefers one failure mode over another.

Eventhough, researchers identified that the predominant degradation mechanisms for a battery failure include corrosion of the positive electrode, irreversible hard sulfation on the negative electrode, water loss, degradation of the active material, and short-circuits [30]–[32]. Further, it is observed that the main cause for the battery failure is sulfation. Sulfation is the crystallization of lead sulfate into a form that is no longer electro-active. The lead sulfate formed in a fresh battery is coarse and porous. This lead sulfate can be easily converted back to lead dioxide, lead and sulfuric acid. This lead sulfate becomes harder and finer after so many charge/recharge cycles, and can’t be easily converted back to lead dioxide, lead and sulfuric acid. The unconverted lead sulfate crystals significantly reduces the active surface area, and act as an insulator and prevents current flow to the electrode surface on which they lie. These unconverted lead sulfate also leads to capacity loss due to significant loss
of active material. David et.al. [33] discovered that one of the reasons for the capacity loss is due to the expansion of the positive active material during cycling. The danger of expansion rate and capacity loss is greater with deeper and the positive active material during cycling. The danger of the reasons for the capacity loss is due to the expansion of active material. Lam et al. [33] discovered that one of the reasons for the capacity loss is due to the expansion of the positive active material during cycling. The danger of expansion rate and capacity loss is greater with deeper and rapid discharges. The resistance increases in active material with expansion, as the conductivity between the individual PbO₂ particles is lost [33].

Authors in [34], [35], conclude that high rate charging-discharging at partial state of charge leads to the progressive accumulation of lead sulfate on the negative plates. Lam et al. [35], performed teardown analysis on batteries and identified that negative plate sulfation is one of the most prominent aging mechanisms for lead acid batteries. This is because the lead sulfate formed at negative plate cannot be converted efficiently back to sponge lead during charging. Eventually, the layer of lead sulfate develops to such extent that the effective surface area of the plate is reduced markedly. The distribution of lead sulfate across the cross-section at the central bottom of negative and positive plates are shown in Fig. 2 for both charged and discharged states. These results shows that, significant quantity of lead sulfate crystals are still present at negative plate compared to positive plate after recharging, which is undesirable.

The discharge and charge processes of the negative plate can be expressed by the following chemical equalitions,

Discharge process:

\[
Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^- \quad (1)
\]

\[
Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4 \quad (2)
\]

Charge process:

\[
PbSO_4 \leftrightarrow Pb^{2+} + SO_4^{2-} + 2e^- + H^+ \quad (3)
\]

\[
Pb^{2+} + SO_4^{2-} + 2e^- + H^+ \rightarrow Pb + HSO_4^- \quad (4)
\]

During discharge, the conversion of Pb to PbSO₄ happens in two steps, i.e. dissolution and depositions processes (1) & (2). The dissolution process is an electrochemical reaction, which involves electron transfer. The rate of the electrochemical reaction depends on diffusion of HSO₄⁻ and available active surface area of Pb. On the other hand, deposition process is a chemical reaction which depends on the acid used. The solubility of PbSO₄ in the acid reaches a maximum value at a concentration of 10wt. % H₂SO₄, and then decreases rapidly with further increase in concentration. Therefore, Pb²⁺ will precipitate as PbSO₄ at concentrations above the solubility curve. Similarly, during charging the conversion of PbSO₄ to Pb happens in two steps, i.e. dissolution and depositions processes (3) & (4). But these reactions are differ from discharge reactions, in this case dissolution is chemical reaction, whereas the deposition is electrochemical reaction.

During the initial stages of the discharge, electron transfer occurs both on the surface and in the interior of the negative plate. Later due to the decrease in acid levels in the interior of the plate, the reaction in the interior plate will stop, while charge transfer continues on the surface. The flow of acid and ionic species to (and from) the interior of plate is decided by the Pb paste density. Thus for the given paste density, the depth to which PbSO₄ penetrates depends on the discharge rate [35]. Under low discharge rate, the dissolution rate of Pb²⁺ is slow. Therefore, the deposition of Pb²⁺ on PbSO₄ occurs slowly due to the low supersaturation of Pb²⁺. Since the deposition rate is slow, newly formed PbSO₄ tends to precipitate preferentially on the already deposited lead sulfate, resulting continuous growth of PbSO₄ in various sizes of discontinuous crystals. This form of lead sulfate is desirable as it provides an open structure that facilitates the ingress of HSO₄⁻ ions. Therefore, the ionic transfer can proceed deep into the interior of the plate resulting evenly distribution of PbSO₄ throughout the cross-section of the negative plate, as shown in Fig. 3 (a). On contrary under high discharge rate, the diffusion process proceeds so rapidly such that the diffusion rate of HSO₄⁻ cannot catch up with the consumption rate, resulting formation of PbSO₄ mainly on the surface of the plate. Further, high discharge rate generates a very high supersaturation of Pb²⁺. Therefore, the PbSO₄ will precipitate quickly on any available surface (either on Pb or already formed PbSO₄), leading to formation of compact layer of tiny lead sulfate crystals on the plate. This will reduce the effective surface area for electron transfer and will also hinder the diffusion of HSO₄⁻ into the interior of the plate as shown in Fig. 3 (b). Under such conditions, the discharge reaction cannot proceed into the interior, but stops at the surface of the plate and at the walls of the pores.
In summary, battery discharging with high discharge rate prone to have more PbSO₄ formation on negative plate as explained above. Moreover, the formation of PbSO₄ is such that effective surface area for electron transfer is reduced more with high discharge rate. After repeated charge and discharge cycles the deposit of lead sulfate increases significantly and reduces the battery capacity as shown in Fig. 4. Therefore, in this paper we have proposed a new control algorithm which will control the battery charge and discharge rates in conjunction with supercapacitor to reduce sulfation and hence improve the battery life.

III. GENERAL ANALYSIS OF HESS

To demonstrate the feasibility of the proposed control scheme, a standalone PV system with HESS is considered, as shown in Fig. 5. The system consists of PV panel, battery, supercapacitor and power electronic converters. The PV panel is connected to DC grid by using a boost converter. The boost converter is controlled such that, the PV panel always operates at its maximum power generation. Battery and supercapacitors are connected to DC grid using the bi-directional buck-boost converter to form the HESS. Here, the HESS is used to maintain the constant DC grid voltage (Vₒ), without getting affected due to mismatch between the generation and the demand. When the demand is more than the generation, Vₒ would drop from its reference value, consequently HESS will discharge to provide the surplus demand. Similarly, when the demand is less than the generation, Vₒ would increase from its reference value, consequently HESS will charge to absorb the surplus power. The DC loads and the AC system are represented with equivalent DC load resistance R connected to the DC grid.

Fig. 3. Schematic representation of the distribution of PbSO₄ in a negative plate subjected to: (a) low discharge rate or (b) high discharge rate [35].

Fig. 4. Capacity loss resulting from consecutive charges and discharges [28].

Fig. 5. Equivalent system configuration of DC grid.

Fig. 6 shows the schematic of conventional controller for HESS. The control scheme maintains the grid voltage (Vₒ) at its reference value (V_ref). Here, the change in power demand fluctuations are reflected in terms of Vₒ. The error in voltage is given to the PI controller. The PI controller generates the total power (P_tot_ref) supplied by the HESS in order to account for the power demand fluctuations. This total power is decomposed into low and high frequency components. The low frequency component is given as reference (P_B_ref) to the battery converter, whereas the high frequency component is given as reference (P_SC_ref) to the supercapacitor converter. With this controller, at any point of time, the mismatch in generation and demand (ΔP_D) is supplied by the battery and/or the supercapacitor, which can be described by the following equation

\[ \Delta P_D(t) = P_B(t) + P_{SC}(t), \] (5)

where \( P_B \) is power supplied by the battery, and \( P_{SC} \) is power supplied by the supercapacitor.
Fig. 7 shows the typical response curves of the PI controller for an increase in demand ($\Delta P_L$) scenario. The area under these curves give the energy supplied by the respective ESS. For example, the energy discharged by the battery is given by

$$E_B = \int_0^T P_B \, dt = \int_0^T V_B I_B \, dt,$$

where $V_B$ is voltage, $I_B$ is current and $P_B$ is power of battery. Depending on the energy levels, the SOC of the ESS increases or decreases or remains within the limits. The % SOC of the battery is given as [37]

$$\% \text{SOC} = \left(1 - \frac{1}{Q} \int I_B \, dt\right) \times 100,$$

where $Q$ is capacity of the battery, and $I_B$ is positive if battery is discharging, and negative if battery is charging. Since the energy and the SOC's are functions of the $I_B$, the SOC of the battery can be expressed as a function of the energy,

$$SOC = f(E_B).$$

Therefore, the state of charge will depend on the energy stored/discharged from the battery, and hence on the power path (trajectory) followed by the battery in order to meet the specific power demand.

During transient period, the power trajectory of the battery completely depends on the PI parameters, the error input to the PI controller and the controller algorithm used. In general, the power trajectory will be non-linear, as shown in Fig. 7. To demonstrate the effect of power trajectory on the battery energy storage, let us assume that the maximum discharge rate allowed for the battery by the manufacturers is $m_{max}$, and the battery response to change in load demand is linear, rather than nonlinear. Fig. 8 shows the three possible power profiles followed by the battery to meet the load demand of $\Delta P_L$. As shown in Fig. 8 (a), Profile-1 supplies the load demand at zero discharge rate for a period of $t_M$. After that, it discharges at the maximum discharge rate ($m_{max}$) allowed for the battery by the manufacturers. Profile-2 supplies the load demand at linear rate ($= \Delta P_L/T$) depending on the load demand. Similarly, Profile-3 supplies the load demand at maximum discharge rate ($m_{max}$) initially, and after meeting the required load demand, it supplies the load at zero discharge rate. Among the three profiles, Profile-2 is supplying the load demand with less discharge rate. Here, Profile-1 and Profile-3 discharge at the maximum discharge rate. Therefore, all the non-linear power profiles generated by the PI controller lies in between the Profile-1 and 3, for the given load demand ($\Delta P_L$) and the settling time ($T$). Energy delivered by the battery for these power profiles is shown in Fig. 8 (b). It shows that, for a specific load demand and settling time, the energy delivered by these profiles is in the following order: Profile-1 < Profile-2 < Profile-3. Among these three profiles, Profile-3 discharges more energy with high discharge rate compared to the remaining profiles, which is undesirable. So Profile-3 is neglected from the study. But Profile-2 delivers more energy with less discharge rate, whereas Profile-1 delivers less energy with high discharge rate. Therefore, there a trade-off condition should exist between the discharge rate and the energy discharged. Therefore, Profile-1 and 2 are considered in our study to propose a new energy management control scheme to optimize the rate-limit as well as the energy, which is explained in the subsequent section.

IV. TWO STAGE RATE LIMIT CONTROL

In the proposed control scheme, the fundamental idea of battery supplying the low frequency power component and supercapacitor supplying high frequency power component is retained. However, an additional feature called adaptive rate limit control is added to the conventional PI controller, as shown in Fig. 9.

To demonstrate the proposed control scheme let us make the following assumptions:

1) the maximum allowed charge/discharge rate of the battery system is $m_{max}$,
2) the positive polarity is used for indicating discharging and negative polarity is used for indicating charging of the battery,
3) the difference in load demand and battery power is supplied by the supercapacitor, $P_{SC}(t) = \Delta P_{L}(t) - P_{B}(t)$,
4) power electronic converters are perfectly tuned to track the reference powers, and
5) SOC of the supercapacitor is within the limits throughout the operation.

The idea of the proposed rate limit control scheme is explained by inserting a new power profile, Profile-opt, with variable two stage rate-limit ($m_1$ and $m_2$), in between the Profile-1 and 2, as shown in Fig. 10. The power delivered by Profile-1 is defined as

$$P_{B1}(t) = \begin{cases} 0 & \text{for } 0 < t \leq t_M \\ m_{\text{max}}(t - t_M) & \text{for } t_M < t < T \end{cases} \quad \text{(9)}$$

where, $T$ is the settling time and

$$t_M = T - \frac{\Delta P_{L}}{m_{\text{max}}} \quad \text{(10)}$$

The power delivered by Profile-2 is defined as

$$P_{B2}(t) = m_{\text{lin}}t \quad \text{(11)}$$

where,

$$m_{\text{lin}} = \frac{\Delta P_{L}}{T} \quad \text{(12)}$$

Here, the concept is explained for increase in load demand, i.e., discharging the battery. The same explanation is valid for decrease in load demand, i.e., charging the battery. Profile-1 follows the path AEC with rate-limit of $m_{\text{max}}$. Profile-2 follows the path AC with rate-limit of $m_{\text{lin}}$ and Profile-opt follows the path AFC with rate-limits of $m_1$ and $m_2$. The rate-limits $m_1$ and $m_2$ are defined as,

$$m_1 = \frac{P_1}{t_1}, \quad \text{(13)}$$
$$m_2 = \frac{P_2}{t_2}, \quad \text{(14)}$$

where,

$$P_2 = \Delta P_{L} - P_1, \quad \text{(15)}$$
$$t_2 = T - t_1. \quad \text{(16)}$$

The range of these rate limits are given as

$$0 \leq m_1 \leq m_{\text{lin}}, \quad \text{(17)}$$
$$m_{\text{lin}} \leq m_2 \leq m_{\text{max}}. \quad \text{(18)}$$

The power delivered by Profile-opt is defined as

$$P_{B_{\text{opt}}}(t) = \begin{cases} m_1t & \text{for } 0 < t \leq t_1 \\ P_1 + m_2(t - t_1) & \text{for } t_1 < t < T \end{cases} \quad \text{(19)}$$

The energy stored by the Profile-1 is given as

$$E_{B1} = \text{Area of } \Delta EBC = \frac{1}{2}(T - t_M)\Delta P_{L}. \quad \text{(20)}$$

The energy stored by the Profile-2 is given as

$$E_{B2} = \text{Area of } \Delta ABC = \frac{1}{2}T\Delta P_{L}. \quad \text{(21)}$$

Similarly, the energy stored by Profile-opt is given as

$$E_{B_{\text{opt}}} = \text{Area of } ABCFA$$

$$= \text{Area of } \{\Delta ADF + FDBGF + \Delta FGC\}$$

$$= E_{B_{\text{opt1}}} + E_{B_{\text{opt2}}} + E_{B_{\text{opt3}}}, \quad \text{(22)}$$

where,

$$E_{B_{\text{opt1}}} = \frac{1}{2}t_1P_1 = \frac{1}{2}m_1t_1^2 = \frac{P_1^2}{2m_1}, \quad \text{(23)}$$
$$E_{B_{\text{opt2}}} = \frac{1}{2}t_2P_2 = \frac{1}{2}m_2t_2^2 = \frac{P_2^2}{2m_2}, \quad \text{(24)}$$
$$E_{B_{\text{opt3}}} = t_2P_1 = m_1t_1t_2 = \frac{P_1P_2}{m_2}. \quad \text{(25)}$$

The proposed control scheme is designed such that the following three optimization conditions are satisfied:

1) Energy stored/discharged ($E_{B_{\text{opt}}}$) during the transient period is optimized,
2) Maximum charge/discharge rate ($m_2$) is optimized, and
3) The duration of time ($t_2$) for which battery charges/discharges at its optimized maximum rate ($m_2$) is optimized.

The optimization problem is divided into two objective functions. In the first objective function, $E_{B_{\text{opt}}}$ and $m_2$ are optimized. In the second objective function $E_{B_{\text{opt}}}$ and $t_2$ are optimized. Finally, the results of the two objective functions are superimposed to get the optimal point ‘F’, as shown in Fig. 10.
A. Objective Function I - Optimization of $E_{B_{opt}}$ and $m_2$

Let us assume that $t_1$ and $t_2$ are kept constant for the given operating conditions. With this assumption, (23) - (25) can be expressed as,

$$E_{B_{opt1}} \propto P_1 \propto m_1,$$  
$$E_{B_{opt2}} \propto P_2 \propto m_2,$$  
$$E_{B_{opt3}} \propto P_1 \propto m_1.$$  

From (27), minimization of $m_2$ indicates the minimization of $E_{B_{opt2}}$. As $m_2$ is minimized, the $P_1$ associated with the proposed profile increases according to (14) and (15), which in turn increases $E_{B_{opt1}}$, as given in (26). But to minimize the total energy discharged, $E_{B_{opt1}}$ has to be minimized. Therefore, the objective function can be defined as

$$f_d(m_1, m_2) = \min \{E_{B_{opt2}} - E_{B_{opt1}}\}. \quad (29)$$

Similarly, let us assume that $P_1$ and $P_2$ are kept constant for the given operating conditions. With this assumption, (23) - (25) can be expressed as,

$$E_{B_{opt1}} \propto t_1 \propto \frac{1}{m_1},$$  
$$E_{B_{opt2}} \propto t_2 \propto \frac{1}{m_2},$$  
$$E_{B_{opt3}} \propto t_2 \propto \frac{1}{m_2}. \quad (32)$$

From (31), minimization of $m_2$ implies that the $t_1$ associated with the proposed profile decreases according to (13)-(15), which in turn decreases $E_{B_{opt1}}$ as given in (30). Therefore, to minimize the total energy discharged; the objective function can be defined as

$$f_b(m_1, m_2) = \min \{E_{B_{opt1}} - E_{B_{opt2}}\}. \quad (33)$$

$f_a$ and $f_b$ are same objective functions with difference in polarity. Therefore, from (29) and (33), the first objective function can be defined as

$$f_1(m_1, m_2) = \min \{E_{B_{opt1}} \sim E_{B_{opt2}}\} \quad (34)$$

subject to (17) and (18).

B. Objective Function II - Optimization of $E_{B_{opt}}$ and $t_2$

Let us assume that $P_1$ and $P_2$ are kept constant for the given operating conditions. From (32), minimization of $t_2$ indicates minimization of $E_{B_{opt3}}$. As $t_2$ is decreased, $t_1$ increases according to (16), hence the energy associated with it $E_{B_{opt1}}$ as given in (30). Therefore, to minimize the total energy discharged, the objective function can be defined as

$$f_{c}(m_1, m_2) = \min \{E_{B_{opt3}} - E_{B_{opt1}}\}. \quad (35)$$

Similarly, from (32), minimization of $m_2$ indicates the maximization of $E_{B_{opt3}}$. As $m_2$ is minimized, the $t_2$ associated with the proposed profile increases, which in turn decreases $t_1$ and hence $E_{B_{opt1}}$. Therefore, to minimize the total energy discharged; the objective function can be defined as

$$f_d(m_1, m_2) = \min \{E_{B_{opt1}} - E_{B_{opt3}}\}. \quad (36)$$

$f_c$ and $f_d$ are same objective functions with difference in polarity. Therefore, from (35) and (36), the second objective function can be defined as,

$$f_{II}(m_1, m_2) = \min \{E_{B_{opt1}} \sim E_{B_{opt3}}\} \quad (37)$$

subject to (17) and (18).

C. Solution of Objective Functions:

The ideal solution at which the optimal point occurs for objective function I is obtained by equating (34) to zero. The optimal power at which $(E_{B_{opt1}} \sim E_{B_{opt2}}) = 0$ occurs is derived as,

$$P_1 = \frac{\Delta P_L(T - t_1)}{T}. \quad (38)$$

The locus of the objective function I is shown in Fig. 11 (a). The time interval satisfying the objective function I is obtained by solving (9), (11) and (38) with extreme limits of $m_{lin}$ and $m_{max}$, as shown in Fig. 11 (a). The time interval is defined as

$$t_{I\_lin} \leq t_1 \leq t_{I\_max}. \quad (39)$$

where,

$$t_{I\_lin} = \frac{T}{2}, \quad (40)$$

$$t_{I\_max} = \frac{T^2}{2T - t_M}. \quad (41)$$

The corresponding powers are given as,

$$P_{I\_lin} = \frac{\Delta P_L}{2}, \quad (42)$$

$$P_{I\_max} = \frac{\Delta P_L(T - t_M)}{2T - t_M}. \quad (43)$$

Similarly, the ideal solution at which the optimal point occurs for objective function II is obtained by equating (37) to zero. The optimal power at which $(E_{B_{opt1}} \sim E_{B_{opt3}}) = 0$ occurs is derived as,

$$P_1 = \frac{\Delta P_L}{3}. \quad (44)$$

The locus of the objective function II is shown in Fig. 11 (b). The time interval satisfying the objective function II is obtained by solving (9), (11) and (44), with extreme limits of $m_{lin}$ and $m_{max}$, as shown in Fig. 11 (b). The time interval is defined as

$$t_{II\_lin} \leq t_1 \leq t_{II\_max}, \quad (45)$$

where,

$$t_{II\_lin} = \frac{T}{3}, \quad (46)$$

$$t_{II\_max} = \frac{T + t_M}{3}. \quad (47)$$
D. Limitation of Proposed Scheme:

Based on the change in load demand and settling time, the proposed control scheme has operating point limitation. The limitation has been derived by considering the rate-limit of the \( m_2 \) should not be more than maximum allowable rate limit of the battery provided by manufacturer \( m_{\text{max}} \). Therefore, it is given as

\[
m_2 \leq m_{\text{max}}.
\]

The corresponding power is given as

\[
P_{t_{\text{lin}}} = P_{t_{\text{max}}} = \frac{\Delta P_L}{3}.
\]  

(48)

The optimal operating point satisfying two objective functions is obtained by superimposing the two loci, as shown in Fig. 11 (c). The optimal operating point \( (t_{\text{opt}}, P_{\text{opt}}) \) is obtained by solving (38) and (44). Therefore, the optimal operating point ‘F’ is derived as,

\[
t_{\text{opt}} = \frac{2T}{3};
\]

\[
P_{\text{opt}} = \frac{\Delta P_L}{3}.
\]  

(49)

(50)

Solving (14), (15), (16) and (51) results,

\[
\Delta P_L \leq m_{\text{max}}(T - t_1) + P_1.
\]  

(52)

Substituting (49) and (50) in (52) results,

\[
\Delta P_L \leq m_{\text{max}} \frac{T}{3}.
\]  

(53)

Therefore, from (53), for the given settling time \( T \), the maximum allowed change in load demand is given as

\[
\Delta P_{L_{\text{max}}} = m_{\text{max}} \frac{T}{2}.
\]  

(54)

Similarly, for the given change in load demand, the minimum settling time required is given as,

\[
T_{\text{min}} = \frac{2\Delta P_L}{m_{\text{max}}},
\]  

(55)

V. EXPERIMENTAL STUDY

The proposed control scheme is realized by using the real-time control hardware-in-loop (CHIL), comprising of the OPAL-RT 5600 and the dSPACE 1103, as shown in Fig. 12 (a). The power stage of the PV system consisting of PV panel, battery, supercapacitor and DC/DC converters is modeled in OPAL-RT, as shown in Fig. 12 (b). The specifications of each module is given in Table II. The maximum allowed charging and discharging rates of the battery is assumed as -11.63 kW/sec and +12.93 kW/sec respectively, and the initial state of charge (SOC) of the battery is 50%. The voltage and the current parameters of the PV system, from the OPAL-RT is given as input to the dSPACE controller. The maximum power point tracking (MPPT) algorithm [38], and two stage rate limit controller are designed and implemented in dSPACE, as shown in Fig. 12 (b). These control schemes consist of voltage control loop to regulate the DC grid voltage and current control loops to track the reference currents based on the MPPT algorithm and two stage variable rate-limit controller. The dSPACE controller generates the PWM pulses based on the algorithm, which is given as input to the switches of power stage in OPAL-RT. A first order lowpass filter is considered, such that the corner frequency of low pass filter is nearer to DC frequency (0 Hz) and far away from the switching frequency (10 kHz).
A. Validation of Proposed Scheme for Variations in Generation and Demand

To demonstrate the proposed scheme, sudden increase in load demand and sudden decrease in load demand are considered as shown in Figs. 13 & 14. The proposed scheme is compared with the conventional controller [36]. Fig. 13 shows the OPAL-RT results of increase in load demand. The results describe about the voltages, currents and powers of HESS for 4 study cases (Case0, Case1, Case2 and Case3). In Case0 conventional controller is implemented, and in Case1, Case2 and Case3 proposed control scheme is implemented with different settling times ($T$) of 1 s, 2 s and 3 s for the same test conditions. In all the four cases initially the PV panel is supplying the load demand of 3.6 kW, and at the instant of 1 sec the load demand is suddenly increased to 5.142 kW by decreasing the load resistance from 100 $\Omega$ to 70 $\Omega$. As the load demand is suddenly increased, to compensate the deficiency in generation and to maintain the DC grid voltage at 600 V, the battery and the supercapacitors start to discharge the power. Fig. 13 (a) shows the results of the conventional controller (Case0), and Figs. 13 (b) - (d) show the results of the proposed controller with different settling times of 1 s (Case1), 2 s (Case2) and 3 s (Case3), respectively. From the results it is observed that in Case0 the battery is almost operating at its maximum allowable discharge limit, i.e., at +12.93 kW/s, whereas in Case1 to Case3 the discharge rates ($m_2$) are decreased as shown in Fig. 13. Furthermore, the energy discharged by the battery is more in case of conventional controller, when compared to the proposed one. Therefore, the battery reaches to the lower SOC limit faster in case of conventional controller, as summarized in Table III. From the Table III, it is observed that the state of charge of the battery for Case0 is less than the SOC’s of Case1, Case2 and Case3, it means that relatively more energy is discharged.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cases</th>
<th>$T$ (s)</th>
<th>$m_2$ (kW/s)</th>
<th>$\Delta E$ (kW-s)</th>
<th>% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td>Case0</td>
<td>-</td>
<td>+12.93</td>
<td>+6.17</td>
<td>49.9834</td>
</tr>
<tr>
<td></td>
<td>Case1</td>
<td>1</td>
<td>+3.21</td>
<td>+5.25</td>
<td>49.9859</td>
</tr>
<tr>
<td></td>
<td>Case2</td>
<td>2</td>
<td>+1.00</td>
<td>+4.23</td>
<td>49.9913</td>
</tr>
<tr>
<td></td>
<td>Case3</td>
<td>3</td>
<td>+1.07</td>
<td>+3.22</td>
<td>50.0172</td>
</tr>
<tr>
<td>Charge</td>
<td>Case0</td>
<td>-</td>
<td>-11.63</td>
<td>-6.41</td>
<td>50.0145</td>
</tr>
<tr>
<td></td>
<td>Case1</td>
<td>1</td>
<td>-2.99</td>
<td>-5.41</td>
<td>50.0116</td>
</tr>
<tr>
<td></td>
<td>Case2</td>
<td>2</td>
<td>-1.49</td>
<td>-4.31</td>
<td>50.0086</td>
</tr>
<tr>
<td></td>
<td>Case3</td>
<td>3</td>
<td>-0.99</td>
<td>-3.21</td>
<td>50.0086</td>
</tr>
</tbody>
</table>

Similarly, Fig. 14 shows the OPAL-RT results of decrease in load demand. In this study also, initially the PV panel is supplying the load demand of 3.6 kW. After that, the load demand is suddenly decreased to 2 kW by increasing the load resistance from 100 $\Omega$ to 180 $\Omega$ at the instant of 1 s. As the load demand is decreased there will be surplus generation. Therefore, to maintain the power balance between generation and consumption and to regulate the DC grid voltage at 600 V, the surplus generation is absorbed by battery and supercapacitor. As explained in the above case study, here also the proposed scheme is compared with the conventional controller (Case0), as shown in Fig. 14 (a). In conventional controller the battery is charging power at its maximum limit, i.e., at -11.63 kW/s. Figs. 14 (b) - (d) show the results of the proposed controller with different settling times of 1 s (Case1), 2 s (Case2) and 3 s (Case3) respectively. It shows that in proposed controller battery is charging at lower charging rate compared to conventional one. As a result the energy stored
Fig. 13. OPAL-RT results of increase in load demand: (a) conventional, (b) proposed with $T = 1$ s, (c) proposed with $T = 2$ s, (d) proposed with $T = 3$ s.
Fig. 14. OPAL-RT results of decrease in load demand: (a) conventional, (b) proposed with $T = 1$ s, (c) proposed with $T = 2$ s, (d) proposed with $T = 3$ s.
by battery is lower than conventional one, so that the battery slowly reaches the upper SOC limit, as shown in Fig. 14. These results are summarized in Table III. From the Table III, it is observed that SOC of the battery for conventional PI controller is moving towards the upper limit faster than the proposed scheme.

To demonstrate the effectiveness of control scheme in mitigating the high frequency components a random PV profile is considered as shown in Fig. 15. Here, the irradiance is varying from 150 W/m$^2$ to 800 W/m$^2$. To demonstrate both charging and discharging features of battery the load demand is set to 6 kW by setting the load resistance to 6 Ω. From the results it is observed that the transient components are taken care by supercapacitor and low frequency components are compensated by battery to meet the load demand.

### B. Evaluation of Capacity Loss of Battery

In order to evaluate the capacity loss of the battery the following charge and discharge cycles are considered.

1) Battery is discharged with 15 A for 12 sec and charged with -15 A for 8 sec until the battery reaches 100 % of SOC.

2) Battery is charged with -15 A for 12 sec and discharged with 15 A for 8 sec until the battery reaches specified SOC or depth of discharge DOD.

After that, capacity loss versus number of life cycle data is collected from the datasheet of 6-DZM-14 Lead acid battery

[39]. Based on the data an 4th order polynomial equation is derived using the curve fitting technique in Matlab as given,

$$ f(x) = p_1 * x^4 + p_2 * x^3 + p_3 * x^2 + p_4 * x + p_5 \quad (56) $$

where $f(x)$ is capacity loss of battery and $x$ is number of life cycles. The parameters of the polynomial are,

- for DOD of 30 %: $p_1 = -1.39e-11$, $p_2 = 4.899e-08$, $p_3 = -7.529e-05$, $p_4 = 0.0187$, and $p_5 = 99.99$.
- for DOD of 50 %: $p_1 = -1.41e-09$, $p_2 = 1.677e-06$, $p_3 = -0.0007856$, $p_4 = 0.1007$, and $p_5 = 99.38$.
- for DOD of 80 %: $p_1 = 1.292e-08$, $p_2 = -7.59e-06$, $p_3 = 0.0005853$, $p_4 = 0.05724$, and $p_5 = 100.1$.

Fig. 16 shows the loss of capacity of the battery for both conventional controller and proposed controller. From the results of Fig. 16 (a) it is observed that for the same charge and discharge cycles the capacity is almost same at initial stages, but as time progresses capacity of the battery decreases rapidly with conventional controller compared to proposed controller. As a consequence there is an improvement in number of life cycles over the conventional controller as shown in Fig. 16 (b). Further, it is observed that as DOD increases the capacity...
of the battery decreases fastly and number of life cycles are reduced comparatively.

From the above results, it is observed that the proposed control scheme relatively reduced the charge/discharge rates and energy stored/discharged by the battery. In addition, the charge/discharge rates and change in battery energy further reduced with increase in settling time. As the current charge/discharge rates of battery are low in the proposed scheme, it would expectedly result in reduced current stresses and improvement in life span of battery.

VI. CONCLUSION

A variable two stage rate-limit control has been proposed to optimize the charge/discharge rates and energy stored/discharged by the battery. Two different rate-limits are designed to charge/discharge the power from battery depending on the required load demand and settling time. To verify the effectiveness of the control scheme, it is applied to a standalone PV system with HESS by forming a control hardware-in-loop (CHIL) using OPAL-RT and dSPACE. The results are compared with the conventional control scheme, and it is observed that charge/discharge rates and energy stored/discharged by battery are optimized during transient period compared to conventional scheme. As the charge/discharge rates are optimized, the stress levels on the battery is also optimized, thereby minimizing the life time limiting effects due to high charge/discharge rates. Furthermore, since the energy stored/discharged by the battery gets optimized, the state of charge of the battery is maintained within the limits for longer duration, resulting in reduction of over charging/discharging of the battery. Since the proposed control scheme retains the features of conventional control scheme, the power balance remains unaffected under the steady-state operating conditions with the help of the supercapacitor.

VII. ACKNOWLEDGEMENT

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REFERENCES


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