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New Methodology to Mitigate the Effects of Pulsed Loads in Microgrid Systems

Neethu P Uday[1], Annie P Oommen[2], Neena Mani[3]

P.G. Student, Mar Athanasius College of Engineering, Kothamangalam, Kerala, India [1]

Professor, Mar Athanasius College of Engineering, Kothamangalam, Kerala, India[2]

Assistant Professor, Mar Athanasius College of Engineering, Kothamangalam, Kerala, India[3]

ABSTRACT: Microgrid power systems are becoming increasingly common in a large number of applications. In this paper, the mitigation of the adverse effects of pulsed power loads on the microgrid systemsis considered. In microgrid power systems, pulsed loads are particularly problematic since the total system inertia is finite. Examples include ships and aircraft with high power radars, pulsed weapons, and electromagnetic launch and recovery systems. In these systems, energy is collected from the system over a finite time period, locally stored, and then rapidly utilized. Herein, a new strategy, Profile Based Control, to accommodate these loads is presented. This strategy is based on identifying the optimal charging profile. Also, later onwards, this new strategy is combined with load coordination. And it is found that current waveform is more smoothened and the output power is improved from 2489W to 3712W.

KEYWORDS: Pulsed load, Microgrid, Load coordination, Profile Based Control

I. INTRODUCTION

Microgrid power systems with Pulsed Power Loads (PPLs) are of significant interest in marine and aerospace applications. In these applications pulsed loads include high power radars, electromagnetic launch and recovery systems, and weapons such as rail guns. Particle accelerator and laser experiments are examples of pulsed loads in utility class systems. These advanced loads usually consume large amount of power in a very short period of time. They will show significant nonlinear characteristics. It is often the case in such loads that a load specific energy storage element is charged over a finite interval of time, and then rapidly discharged. The charging of the energy storage device is an intermittent load which disturbs the power system. The power requirements of such loads can range from kilowatts to megawatts with a charge interval of the order of seconds to minutes [3]. The discharge duration is normally much shorter, and is often essentially instantaneous compared to the charge interval wherein energy is accumulated from the power system. The goal is to minimize the system impact of these PPLs. Perhaps the most straightforward way to control PPLs of this type is through the use of Limit Based Control (LBC). The philosophy of LBC is to charge the energy storage element as rapidly as possible subject to current and power limits. It is shown that the strategy is simple and effective. But it is also rather disruptive to the system.

One method to reduce the impact of pulsed loads is through the introduction of supplementary energy storage devices like flywheels [2]. But such an approach adds mass and expense to the system. Another method to reduce the disruption caused by PPLs is through the load coordination. In this approach, the base load is shed in order to accommodate the pulsed load, so that the total system load remains constant. Such an approach is considered in [4], [6], and [7], and requires that adequate base load already exists, and that the base load is not critical. When these conditions are met, this strategy is effective. But, there are many cases in which these requirements are not met. As an alternative to LBC, auxiliary energy storage, and coordination strategies, a Trapezoidal Based Control (TBC) was modelled in [8]. This control was based on using trapezoidal load profile. The parameters governing the shape of the trapezoid were selected so as to minimize the disruption caused by the pulsed load. However, this report assumed that the trapezoidal power profile was the optimal shape. Herein, it is shown that this is simply not the case. As an alternative, a generalized Profile Based Control (PBC) is presented. In this scheme, it is assumed that there is a requirement to accumulate a set amount of energy from the system in a set amount of time. The control is designed to achieve these requirements in

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such a way as to cause a minimal disruption on the power system. The optimal shape for the power profile is derived, and is shown to be nontrapezoidal, as used in [8]. It should be observed that the presented algorithm could be used in conjunction with load coordination, if desired.

The PPL in this system uses capacitive energy storage, though the control presented here is not limited to this form. This development begins with the presentation of a metric to describe the disturbance caused by a PPL. This metric is then used to obtain an optimal power trajectory. A state feedback based approach to achieving this desired trajectory is then set forth. This is a critical step because it leads to robustness. Load coordination is employed to make the total system load constant by shedding the base load in accordance with the variation of pulsed power load. Using the simulations, the PBC combined with load coordination is shown to contain much less ripples than the PBC based PPL. And also, in simulations it is found that the output power is improved for the latter method.

II. SYSTEM DESCRIPTION

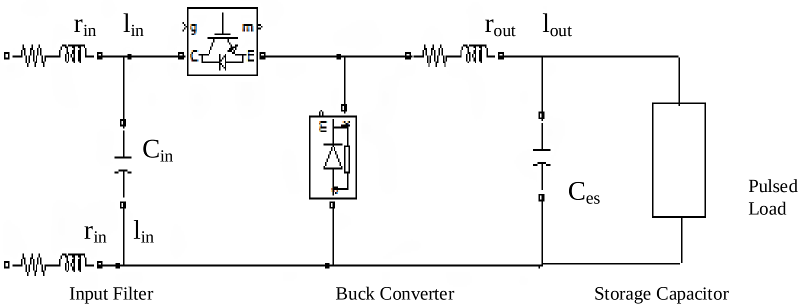

Fig.1 MVDC PPL system schematic

The circuit topology of the PPL is depicted in Fig. 1 and has two parts - an energy accumulation and storage circuit (consisting of an input filter, buck converter, and storage capacitor) and an impulse load. The input filter is designed to reduce the high frequency current ripple associated with the buck converter from entering the power distribution system. The buck converter regulates the current so as to charge the energy storage capacitor according to the desired profile. The impulse load is the application which actually uses the energy; the duration of this use is normally instantaneous compared to the duration of the charge cycle.

The pulsed load is that part of the PPL which discharges the capacitor. The storage capacitor used here plays an important role in PPL. This paper is entirely concerned with the generation of capacitor current and thereby reducing the impulse response obtained during charging and discharging of capacitor. In the circuit, the energy storage capacitor is emulated so that the energy storage does not need to be physically achieved, and to make it easier to achieve the appearance of a rapid discharge. Also, the presented scheme can be implemented along with load coordination technique. In load coordination method, the total system load is made constant by shedding the base load in accordance with the variation of pulsed power load. The PBC combined with load coordination technique is found to be containing much less ripples than the PBC based PPL. And also, it is found that the output power is improved for the latter method.

A. Disturbance Metric

It can be seen that the PPL causes significant disturbance to the system. In order to reduce this impact, a metric to describe the disturbance is first introduced. For this purpose, the metric proposed in [8] is reviewed and utilized. For design purposes, it is convenient to define a metric that is only a function of the PPL. The disturbance of a PPL on a system is related to its time power profile. This profile is denoted as $P_p(t)$ and is referred to as the power trajectory herein. The power trajectory must satisfy several constraints. First, the power trajectory must be such that the desired energy is obtained. Thus

$$\int_0^{Tp} Pp(t)dt = \Delta E_p^* \qquad (1)$$

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where ΔE_p^* is the incremental additional energy to be stored in the energy storage element during the charge cycle, and is the period of the charge cycle. Note that prior to the charge cycle, the amount of energy stored is not necessarily zero. Second, it is desirable that the power trajectory is a continuous function of time. Thus it is required that

$$P_p(t) \in C_0 \tag{2}$$

where C_0 is the set of continuous functions. This facilitates implementation in the presence of parasitics, and also limits the bandwidth of PPL disturbances on the system. This requirement is thus coupled with the requirement that

$$P_p(0) = P_p(T_p) = 0 \tag{3}$$

Finally, it is desired that the system disturbance caused by the trajectory is minimized. Hence, one philosophy for a disturbance metric is to define the metric in terms of the time rate of change of the power trajectory. To this end, the disturbance metric [8] is proposed as,

$$dp = \sqrt{\frac{1}{Tp}\int_0^{Tp}\left(\frac{dPp(t)}{dt}\right)^2 dt} \tag{4}$$

In this, $\frac{dPp(t)}{dt}$ is the time rate of change of power into the PPL. It is convenient to normalize quantities of interest so that the results are readily scaled. For this purpose, using the approach of [8], the base energy will be defined as the desired incremental additional energy to be stored. For the purposes of illustration, consider the case in which the energy storage mechanism is capacitive.

B. Normalization

Let v_c, v_{c0}, v_{cf}, i_c and C denote the energy storage capacitor voltage, the initial capacitor voltage, the final capacitor voltage at the end of the charge cycle, the capacitor current, and the capacitance respectively. The objective is to formulate a capacitor current command i_c^* so that an additional amount of energy ΔE_p^* is stored in the capacitor over a duration T_p. The energy stored in the capacitor may be expressed as,

$$Ep = \frac{1}{2}Cvc^2 \tag{5}$$

It follows that the normalized energy may be expressed as,

$$\hat{E}_p = C\,\frac{Vc2 - Vco2}{2\Delta Ep*} \tag{6}$$

The normalized power command may then be calculated as

$$P_p^* = f_p(\hat{E}_p) \tag{7}$$

The power into the capacitor is expressed,

$$P_c = v_c\, i_c \tag{8}$$

Solving for the current yields

$$i_c = g_p(\hat{E}_p) \tag{9}$$

where,

$$g_p(\hat{E}_p) = \frac{Pp{,}bfp(\hat{E}p)}{\sqrt{vc0^2 + \frac{2Ep*Ep}{C}}} \tag{10}$$

Thus, this final equation could be used to calculate the desired capacitor current command [1]. However, there are two practical problems with doing this. First, if the initial energy is zero the expression is an indeterminate form when the energy stored is zero. If the initial energy is not zero then the initial current command is zero and the capacitor will not charge. In addition, because of losses and nonlinearities in the capacitance, it is possible that the desired final voltage will not be reached. These practical difficulties are circumvented by establishing a low energy threshold and high energy threshold [1] and then calculating the current command as

$$ic^* = \begin{cases} gp(\hat{E}LT) & \hat{E}p < \hat{E}LT \\ gp(\hat{E}p) & \hat{E}LT \le \hat{E}p \le \hat{E}HT \\ gp(\hat{E}HT) & \hat{E}HT < \hat{E}p \end{cases} \tag{11}$$

This avoids numerical issues and ensures start-up and charge cycle completion, although it does cause a minor deviation from the optimal trajectory. The resulting waveform for i_c^* is depicted in Fig. 2. Recommended values for $\hat{E}_{LT}$ and $\hat{E}_{HT}$ range from 0.01–0.05 and 0.95–0.99, respectively. At this point, a control method derived from the metric to minimize system impact of the PPL has been presented. The control algorithm will now be demonstrated.

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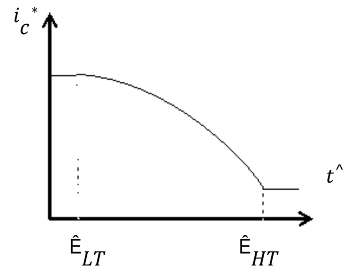

Fig. 2 Optimal generalized waveform i_c^* command.

Fig. 3 depicts the final implementation of the control, which is based on the final equation obtained. The inputs to the control are the measured capacitor voltage, v_c (used to determine the energy stored), and the charge status, e_c. As can be seen, the measured capacitor voltage is filtered. Then, the normalized energy stored is found out using the equation. The normalized energy is then used to determine a preliminary current command. The output of the controller is the capacitor current command given by the final equation or 0 depending on the desired charge status, which is high during a charge cycle and low otherwise.

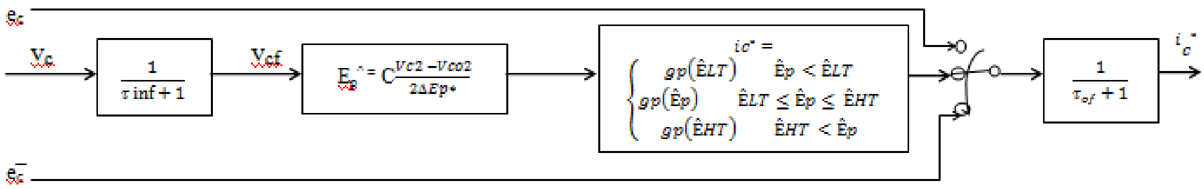

Fig. 3 Profile based control scheme

III. MATLAB/SIMULINK MODEL

This section depicts the performance of the PBC in MATLAB/Simulink environment. The MATLAB/Simulink model employing only the PBC scheme is,

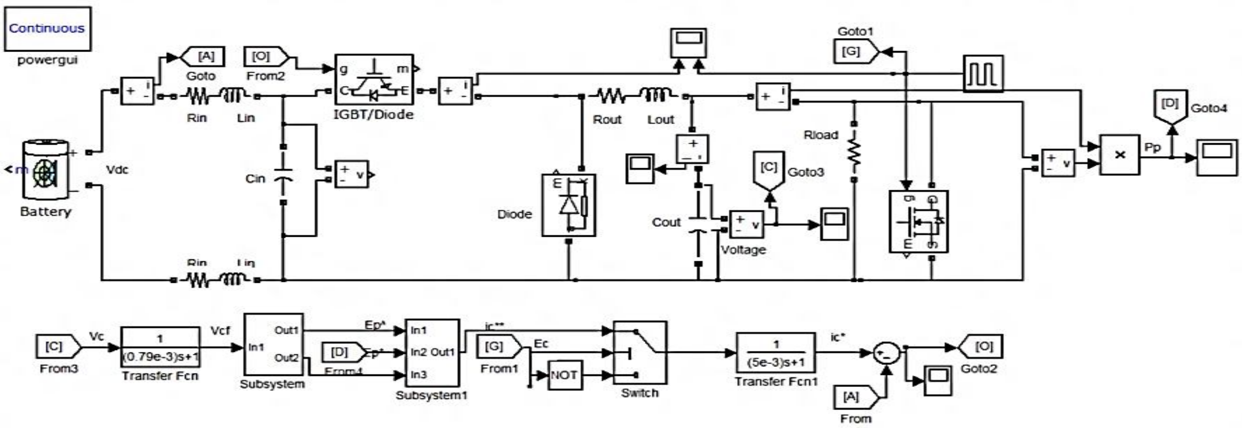

Fig. 4 MATLAB/Simulink model of profile based control (PBC) scheme

The study parameters and conditions for this model are given by,

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TABLE I
SIMULATION PARAMETERS

COMPONENTS	PARAMETER
Input resistor	0.25Ω
Input inductor	0.113mH
Input capacitor	1.4mF
Output resistor	0.1Ω
Output inductor	3mH
Storage capacitor	2.02F

The Profile Based Control (PBC) defines an incremental addition energy value. Figs. 6 and 7 depict the study results for the PBC.

To improve the output of single PBC scheme, it is employed along with load coordination technique and the results are studied using MATLAB/Simulink model. Fig 5 shows the MATLAB/Simulink model of the system employing both PBC scheme and the load coordination method.

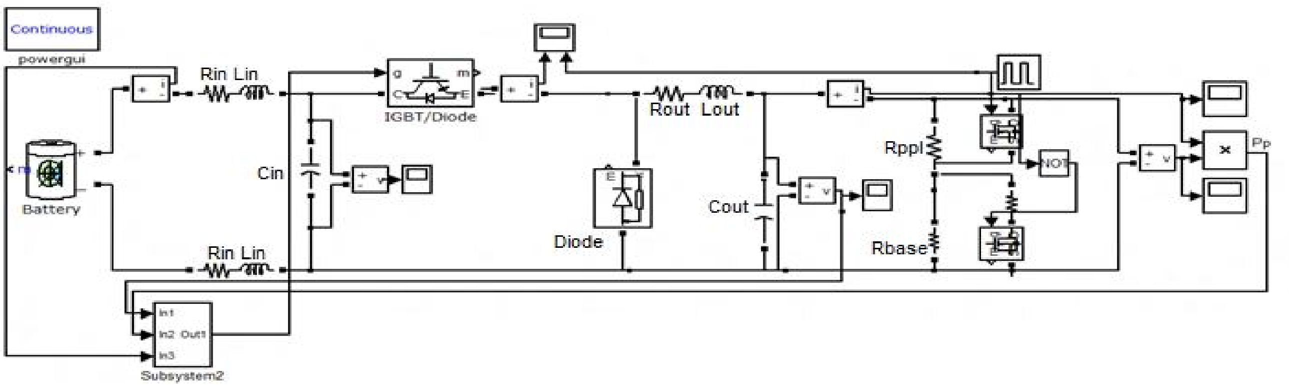

Fig. 5 MATLAB/Simulink model of profile based control (PBC) scheme along with load coordination

When load coordination is employed along with PBC scheme, it is found that the current ripples are reduced and the output power is improved.

IV. SIMULATION RESULTS

The simulation results for the PBC scheme are given by,

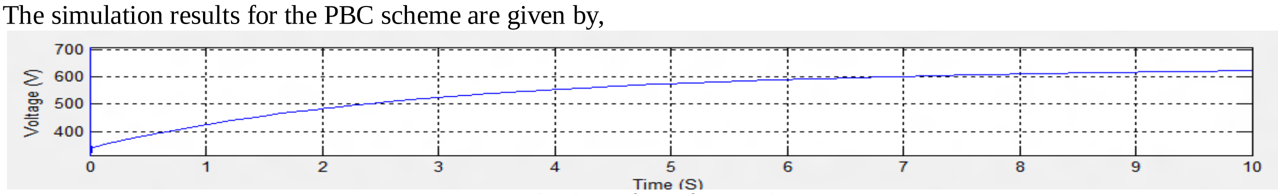

Fig. 6 Simulated waveform of input voltage (V)

In the MATLAB/SIMULINK environment, the input voltage is given in the range of 400V to 600V and the input current is of the order of 100A.

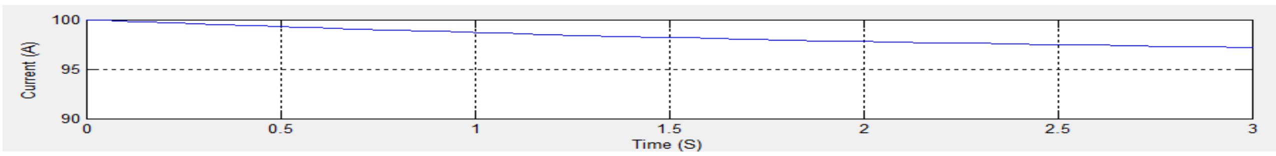

Fig. 7 Simulated waveform of input current (A)

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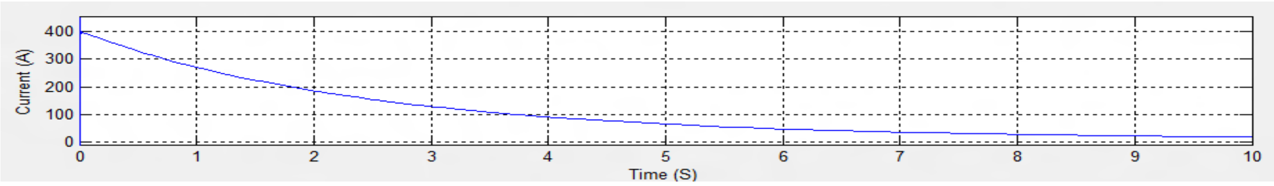

Fig. 8 Simulated waveform of switch current (A)

The output voltage is gradually increasing from 0V to 600V. So, the impact of pulsed load is reduced by using the storage capacitor at the output.

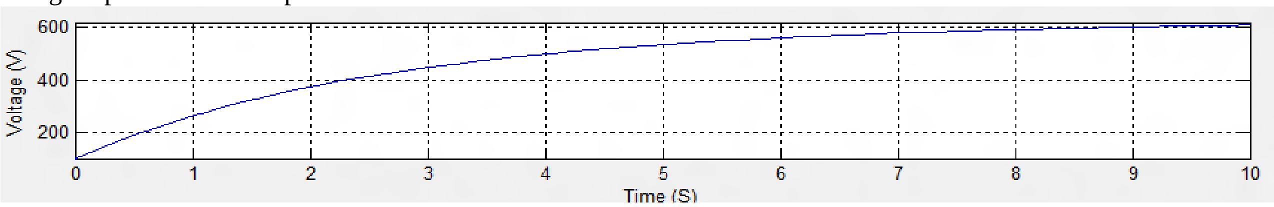

Fig. 9 Simulated waveform of output voltage (V)

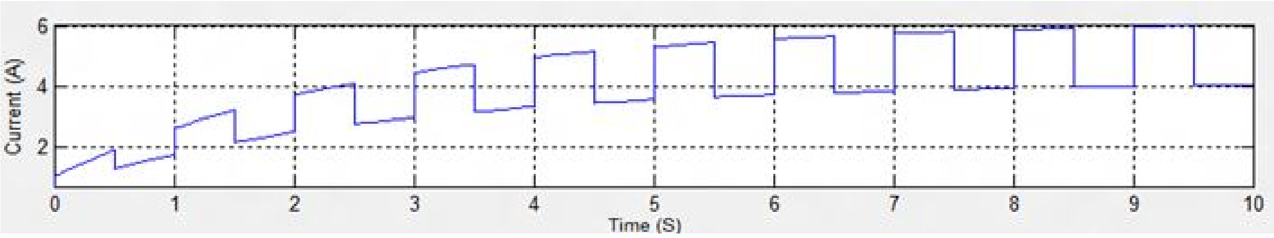

Fig. 10 Simulated waveform of output current (A)

Fig. 6 to Fig. 10 shows the simulation results of system with PBC scheme. As can be seen, the capacitor voltage i.e., the output voltage can be seen torise nearly linearly until the capacitor voltage approaches its final value. The input current closely mimics the shape of the desired power trajectory.

For the same input parameters, the load coordination technique is implemented along with PBC scheme. All the simulation results are same as that shown above except for the output current waveform (Fig. 11).

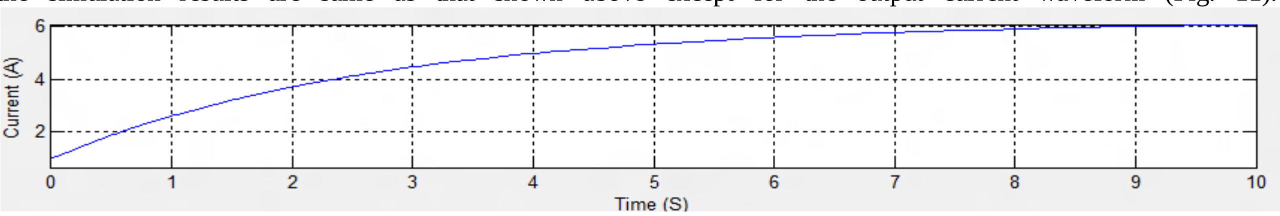

Fig. 11 Simulated waveform of output current (A) for system with load coordination and PBC scheme

It is found that using this technique, we get more ripple free output current and output power is found to be improved from 2489W to 3712W.

V. CONCLUSION

In thispaper, a new scheme named Profile Based Control (PBC), to accommodatethe pulsed loads is presented. This strategy is based on identifying the optimal charging profile. Using simulation it is shown that the PBC strategy is highly effectivein reducing the adverse impact of pulsed power loads. Also, this new strategy iscombined with another

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technique called load coordination. When this Profile BasedControl scheme is employed along with the load coordination technique, the current waveform become much smoother and the output power is improved from2489W to 3712W. The PBC scheme has been shown to offer significant advantages. The advantages of the combination of PBC and load coordination over thesingle PBC scheme have been demonstrated using time-domain simulation. Suggestedfuture work is to study the performance of PBC when the energy storage capacitoris replaced by some other storage provisions like a battery coupled with an inductor.

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