Comparison of Non-Communication based DC Load Shedding Schemes

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***Abstract*—Whenever the total power that can be provided by the distributed energy resources (DERs) is less than the total power demand of the loads, the DC bus voltages start to fall which could lead to power collapse. This paper investigates and compares the performances of the existing non-communication based (decentralized) load shedding schemes in a direct current (DC) microgrid to protect the integrity of the microgrid under a large disturbance. The simulation is carried out in a Matlab environment with various forms of load and distributed energy resources on an IEEE 37 AC Node converted to DC. The findings show that the conventional load shedding scheme could expose critical loads to substantial and lengthy voltage sags. Voltage sags and over-shedding of load could be resolved using combined load shedding scheme. The adaptive schemes minimise the duration and magnitude of voltage drop by utilizing the rate of change of voltage (ROCOV) to achieve a more reliable assessment of the microgrid operating conditions and determine the appropriate load shedding voltage thresholds and time delays. All the schemes could not achieve an optimal load shedding, this work therefore leads to the need for more advanced load shedding schemes that can shed load optimally for future DC microgrids.**

***Index Terms*—DC microgrid, distributed energy resources, DC load shedding**

I. Introduction

The energy demand grows in proportion to the world's population. The development of renewable energy sources (RES) has witnessed tremendous growth in recent years due to the increasing cost of fuel and the need to reduce greenhouse gas emissions. In such a context, many countries have deployed large-scale RES targeting the decarbonisation of produced electrical energy [1]. DC microgrid is an emerging technology that facilitates the integration of distributed energy resources (DERs) in power distribution networks, reduces energy losses, and improves the quality and reliability of the electrical energy supplied to the consumers [2].
The structure of a DC microgrid consists of sources with DC output that are directly connected to the bus while sources with AC output are interfaced to the DC bus via AC/DC converters. Interestingly, in a DC system fewer power converters are required, allowing for size optimization and improvement in overall efficiency. DC microgrid outperforms the AC microgrid in terms of system efficiency and size [3], which also results in reduced investment and operating costs. The protective mechanisms of microgrid ensure that the system's operation is guided by several principles and parameters. Parameters such as voltage and power quality are continuously monitored and controlled by proper monitoring and control systems and procedures [4].

A practical DC microgrid needs an accurate control method to regulate the DC bus voltage and provide sufficient dynamic response to disturbances [5]. Consequently, when the power demand of the loads exceeds the power generation of the DERs, control actions find it difficult to maintain the power balance, and the DERs will fail to regulate the DC bus voltages. Under such conditions, it is necessary to shed some of the loads to protect the DC microgrid integrity [6]–[8]. As a result, the DC microgrid requires an effective load shedding strategy to maintain the DC microgrid's power balance by fast and coordinated shedding of non-essential loads; prevent the microgrid bus voltage from falling below the thresholds that exposes the critical loads to experience significant steady-state voltage deviations; and to minimise voltage sags magnitudes and durations induced by unexpected disturbances [9].

This paper investigates and compares the performances of the existing non-communication-based load shedding schemes in a DC microgrid. A similar comparison was done in the literature [10], but its findings are limited to only conventional load shedding schemes. This paper, therefore, tries to improve on it by comparing all the conventional schemes (comprising of voltage-based, timer-based, and combined schemes) and the adaptive load shedding schemes (comprising of adaptive voltage-based, and adaptive timer-based schemes).The findings of this paper will give an insight on how to improve voltage regulation and optimal load shedding in future non-communication based DC networks.

The paper is structured as follows: Section II presents the overview of DC load shedding schemes. Section III gives the performance evaluation of all the schemes. Section IV provides the conclusions to the paper.

II. DC Load shedding Schemes

DC load shedding schemes can be classified into the Communication based (centralized) and non-Communication based (decentralized) categories.

A. Communication based Load Shedding Scheme

Communication based load shedding schemes consist of a microgrid central controller that processes data from sources of energy and loads and sends commands to them via communication links to maintain power balance in the face of

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large disturbances. An advantage of centralized approach is its ability to shed optimal number of loads owing to its high observability and controllability. The drawbacks of such strategies include complexity, high cost, prone to communications failure, and vulnerable to failure [9]. Therefore, the centralized load shedding schemes are recommended mostly for application in small DC microgrids with compact configurations, where centralized data acquisition is not difficult [9]–[11].

B. Non-Communication-Based Load-Shedding Schemes

The non-communication-based or decentralised load shedding schemes operate on locally measured bus voltages. As a result, these schemes can be applied to large DC microgrids with widely dispersed loads. The decentralized load shedding schemes offer the following advantages: simple implementation, plug-and-play capability, low cost, and high flexibility [10]. The main focus of this work is on the non-communication-based schemes, five of which have been reported in the literature, namely the voltage-based scheme, timer-based scheme, combined voltage and timer-based scheme, adaptive voltage-based scheme, and adaptive timer-based scheme. The theory of operation of the aforementioned schemes is briefly presented in the following subsections.

1) Voltage-based Load-shedding scheme: The voltage-based load-shedding scheme prioritises non-critical loads using different voltage thresholds and sheds a load instantly whenever the voltage observed by that load falls below the equivalent voltage threshold [10], [12]. When the voltage thresholds are too close together, the voltage-based method may lead to needless load shedding, or over-shedding. When the difference between the voltage thresholds is considerable, it can lead to large steady-state voltage deviations, i.e., voltage sag. The loads with lower priorities are assigned higher voltage thresholds and thus are shed faster. In Fig. 1 a representative flowchart of the operation of the voltage-based load-shedding scheme is presented.

2) Timer Based Load Shedding Scheme: The timer-based load shedding strategy [10], [13] uses a common voltage threshold and prioritizes the non-critical loads using different time delays. Whenever the voltage falls below the common voltage threshold for a period of time greater than the time delay, the load is shed. For the scheme to operate effectively the loads with lower priorities are usually assigned lower time delays to effect fast load shedding. The flowchart of the timer-based load-shedding scheme is presented in Fig. 2.

3) Combined Voltage and Timer Based Load shedding Scheme: The combined load shedding scheme utilizes both voltage-based and timer-based algorithms and thus operates whenever either of these two schemes operate. Two different threshold are used on each load, the normal voltage thresholds V_{th} are used for instantly shedding the loads similar to voltage based scheme, in addition i_{th} load is shed when the voltage remains below the common threshold for a time period longer than the corresponding time delay Ti as illustrated in the Fig. 3.

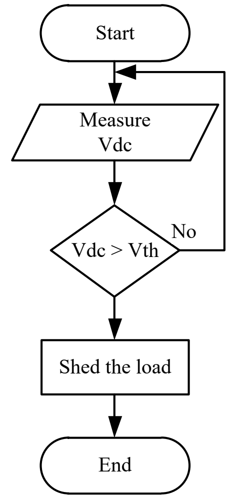

Fig. 1: Flowchart of voltage-based scheme.

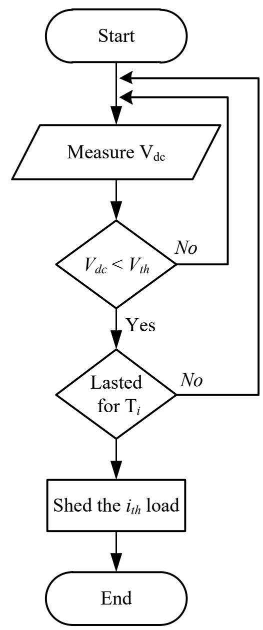

Fig. 2: Flowchart of timer-based scheme.

A combined scheme with appropriately set voltage thresholds and time delays can alleviate the voltage sag problem caused by delayed or missed operation of the voltage-based schemes [10], [14]. The combined scheme is often used as the standard for conventional schemes. The representative flowchart of this method is presented in Fig. 3.

4) Adaptive Voltage Load shedding Scheme: The adaptive voltage load shedding scheme utilizes an adaptive voltage threshold V_{th} that depends on the rate of change of voltage (ROCOV), as defined by:

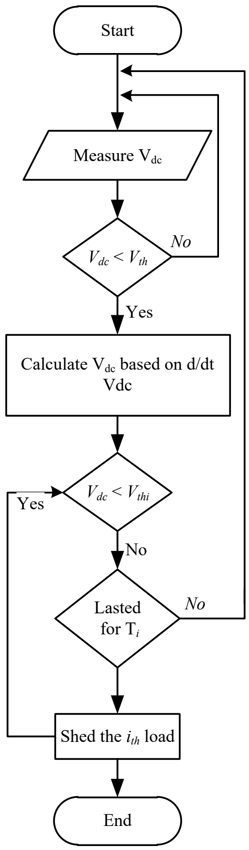

Fig. 3: Flowchart of combined voltage and timer-based scheme.

$$V_{th} = \begin{cases} V_{min}, & -k_1 < \dfrac{dV_{dc}}{dt} \leq 0 \\ V_{min} + m\left(\dfrac{dV_{dc}}{dt} + k_1\right), & -k_2 \leq \dfrac{dV_{dc}}{dt} \leq -k_1 \\ V_{max}, & -\infty < \dfrac{dV_{dc}}{dt} < -k_2 \end{cases} \quad (1)$$

where;

$$m = \frac{V_{max} - V_{min}}{k_1 - k_2} \quad (2)$$

where V_{min} and V_{max} are the minimum and maximum values of the adaptive voltage threshold. The constants k_1 and k_2 identify the values of the ROCOV at which V_{th} reaches the maximum and minimum values [15]. Load shedding takes place whenever the rate of change of voltage (ROCOV) is negative and the locally measured voltage falls below the voltage threshold [16]. When there are large disturbances and the ROCOV is high (above 2.5 V/s), the adaptive voltage threshold V_{th} rises and causes faster load shedding to limit the voltage drop. When the ROCOV is below 0.5 V/s, there is no need for fast load shedding, the voltage threshold is therefore automatically set to a lower value to avoid over-shedding. The representative flowchart of this method is presented in Fig. 4.

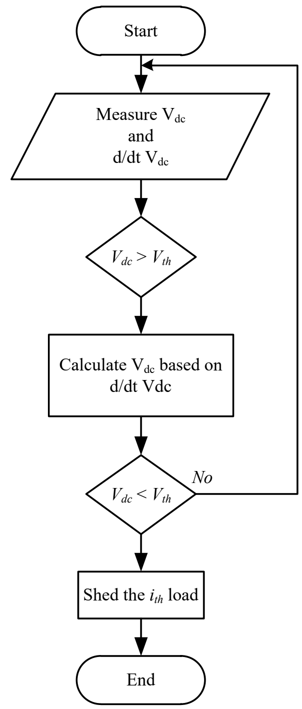

Fig. 4: Flowchart of adaptive voltage scheme.

5) Adaptive Timer based Load shedding: The adaptive timer-based load shedding strategy operates based on the same principle as the conventional timer-based strategy. The improvement of the adaptive strategy is that it tends to shed each non-critical load using a time delay T which adapts to the locally measured ROCOV, as defined by

$$T = \begin{cases} T_{max}, & -k_1 < \frac{dV_{dc}}{dt} \leq 0 \\ \dfrac{T_{max} k_1}{|dV/dt|}, & -k_2 \leq \frac{dV_{dc}}{dt} \leq -k_1 \\ T_{min}, & -\infty < \frac{dV_{dc}}{dt} < -k_2 \end{cases} \quad (3)$$

where: T_{max} and T_{min} are the upper and lower limits of the adaptive time delay, respectively and the constants k_1 and k_2 represent the ROCOV values at which the time delay T becomes equal to T_{max} and T_{min}, respectively. This technique sheds a non-critical load whenever its bus voltage remains below the common voltage threshold for a time period longer than the corresponding adaptive delay, and its ROCOV is negative [16].

III. Performance Evaluation

The system shown in this study represents the IEEE 37-node test feeder which is converted to a ±750 V DC microgrid. It is presented in Fig. 5. The microgrid comprises a set of two photovoltaic (PV) systems, two battery energy storage systems (BESS), and a wind turbine (WT). The microgrid is interfaced with the utility using a grid-tie converter (GTC). Furthermore, the microgrid consists of different loads: Constant Power Loads (CPL), Constant Resistance Loads (CRL) and Constant

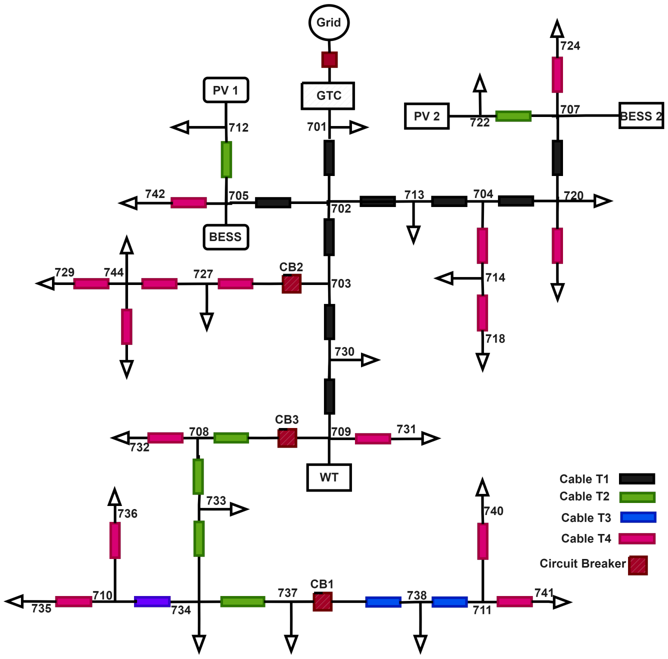

Fig. 5: Single Line diagram of the System

Current Loads (CCL). The system is designed for three-step load shedding where three fast-acting solid-state circuit breakers (SSCB) are used. Tripping each of the CBs results in the shedding of a set of non-critical loads. The sequence is such that circuit breaker CB1 is triggered first whenever load shedding is required, followed by CB2 tripping, and finally, CB3 is triggered if the load remains higher than the generation. The non-critical loads are connected to the circuit breakers as shown in Fig. 5. The total sheddable loads per CB are 148 kW, 148 kW, and 234 kW of non-critical loads respectively. In this study, the voltage drops across the lines are considerable. Therefore, the highest load shedding voltage threshold for all non-critical loads is set at 675 V to prevent load shedding under normal operating conditions. When the bus voltages are over 700 V, the microgrid is deemed to be in normal operating circumstances. The total load of the microgrid is 1260 kW, and the length of the distribution line ranges from the type of cables used. The description, distance, and the line types of the system are shown [10].

The performance metrics of the study are to avoid the system from operating at low voltage, avoid over-shedding by maintaining power balance by disconnecting the smallest number of loads, and fast shedding to minimise the magnitude and duration of the voltage sag. The voltage variations of the critical loads are similar to each other. Therefore, node 702, is used to investigate the performances of the load shedding strategies [14]. For this study, the DC Microgrid is in full islanded mode, and the operating conditions time is set at (t = 1.5 s), which is the time for the introduction of all the disturbances for all the cases. The disturbances is caused by reduction of power generation of the WT from 2 MW to 0.15 MW. The DC bus voltages at the load-side terminals of CB1, CB2, and CB3 is set at 750 V. When the system is in islanded mode, the battery energy system maintains power balance and regulates DC bus voltages.

A. Voltage Based Load Shedding

The voltage-based scheme trips the three CBs whenever the corresponding bus voltages fall below the preset thresholds V_{th_1}, Vth_2, and V_{th_3} respectively. The performance of the voltage-based scheme is investigated using the voltage thresholds V_{th1} = 715 V, V_{th2} = 690 V, and Vth_3 = 675 V. Based on the configuration of the circuit breakers a total of 0.53 MW non-critical loads were shed (148 kW, 148 kW, and 234 kW at CB1, CB2, and CB3 respectively). The corresponding time for tripping the CBs were at: t = 1.54 s, 1.58 s, and 2.0 s as shown in Fig. 6 The last load shedding step is delayed for (0.43s) because the magnitude of imbalance between the load and generation in the microgrid becomes small after the second group of loads were shed. Because of the delayed last load shedding step, the critical loads experience a voltage sag for a relatively long period of time (about 0.43 s) before the last shedding step. The voltage was finally restored at 715 V. The load stands at 0.73 MW which can be accommodated by the generation of 0.815 MW.

B. Timer Based Load Shedding

The timer-based scheme trips the three CBs whenever the corresponding bus voltages remain below the common voltage threshold V_{th} for time periods longer than the delays T1, T2, and T3, respectively. The performance of the timer-based scheme is investigated using V_{th} = 675 V.

Time delays were set at 0.01 s, 0.02 s and 0.03 s. A total of 0.53 MW non-critical loads were shed (148 kW, 148 kW, 234 kW at CB1, CB2, and CB3 respectively). The time for tripping CB1, CB2, and CB3 were set at $t = 1.531$ s, 1.582 s, and 1.593 s as shown in Fig. 7. The voltage seen by the critical loads is regulated at an acceptable voltage of 720 V within a relatively short time (about 0.17 s) after the disturbance. The loads were shed from 1.26 MW to 0.73 MW. The total generation of

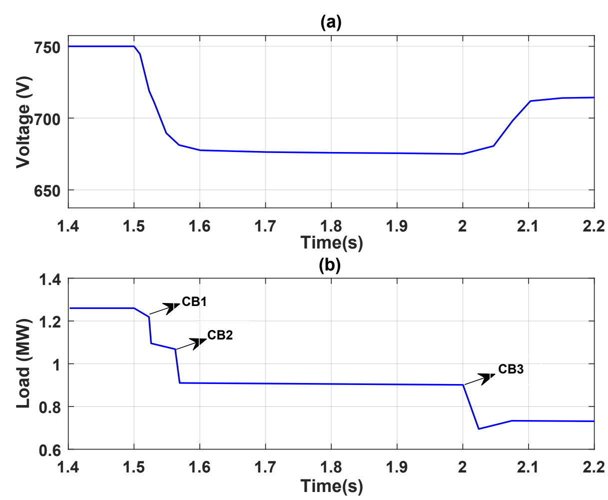

Fig. 6: Performance of Voltage based Scheme; **a)** DC Voltage **b)** Load power

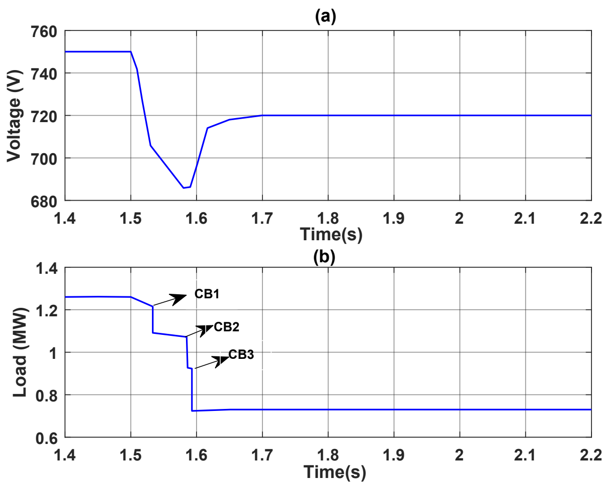

Fig. 7: Performance of Timer based scheme: **a)** DC Voltage **b)** Load power

0.815 MW can now accommodate the load. The timer-based scheme effectively limited the magnitude and time duration of the voltage sags experienced in Fig. 6 due to the short time delays used. However, using excessively short delays may cause unnecessary load shedding [13].

C. Combined Load Shedding

The combined load shedding scheme uses the features of both voltage-based and timer-based schemes, hence it trips the three CBs whenever the corresponding bus voltages falls below the thresholds V_{th_1} = 715 V, V_{th_2} = 690 V, and V_{th_3} = 675 V respectively, or remains below the common voltage threshold Vth = 675 V for time periods longer than T_1 = 0.01 s, T_2 = 0.02 s, and T_3 = 0.03 s respectively. Fig. 8 shows that the combined scheme sheds 0.53 MW non-critical loads by

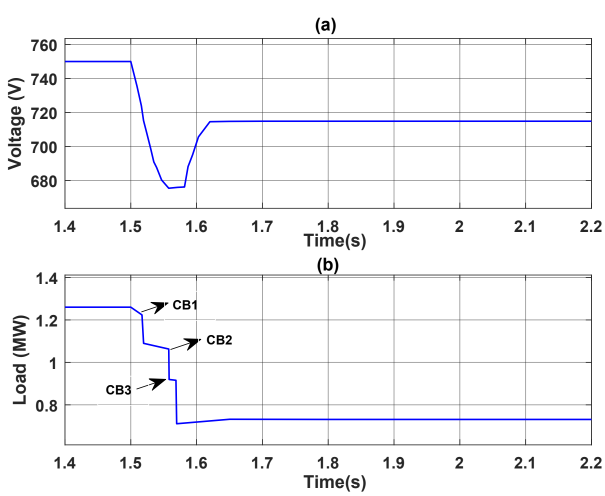

Fig. 8: Performance of Combined based scheme: **a)** DC Voltage **b)** Load power

tripping the CB1, CB2, and CB3 at t = 1.517 s, 1.562 s, and 1.582 s, respectively. As a result, the lowest voltage seen by the critical loads is 685 V and the voltage is regulated at 718 V within a relatively short time (0.16 s) after the disturbance. The results show that the combined load shedding scheme does not suffer from the voltage sag issues as in Fig. 6 and improves the voltage regulation time seen in Fig. 7.

D. Adaptive Voltage Based Load Shedding

The adaptive voltage thresholds used for all three steps of load shedding are automatically set between the range of 715 V to 675 V, this adaptive scheme sheds all three groups of the non-critical loads as soon as the corresponding bus voltages fall below 690 V as shown in Fig. 9. This load shedding scheme trips the CB1 to CB3 at t = 1.516 s, 1.533 s, and 1.533 s, respectively. Due to the faster reaction of the scheme, the voltage does not fall below 690 V and is regulated at 720 V within a short span of 1.2 s after the occurrence of disturbance.

E. Adaptive Timer based Load shedding

The adaptive timer-based scheme sheds two groups of the non-critical loads by tripping the CB1 and CB2 at t = 1.519 s, and 1.665 s, respectively. The CB1 is tripped fast because the magnitude of the corresponding ROCOV is large. Consequently, the voltage seen by the critical loads does not fall below 685 V, and is regulated at 701 V within 0.17 s after the disturbance as shown in Fig. 10. This scheme prevents unnecessary tripping of the CB3 when the ROCOV becomes positive after the second step of load shedding.

Table I below compares the performance of the voltage-based, timer-based, combined-based, and adaptive voltage-based load shedding schemes under the same disturbance. From the results, it could be seen that the adaptive voltage-based scheme sheds loads faster and does not allow the voltage to fall below 690 V while adaptive timer-based sheds loads in two steps.

Fig. 11 summarises the voltage profile of all the load shedding schemes presented. It shows the voltage drops and the voltage at which all the schemes are regulated.

IV. Conclusions

In this paper, the performances of adaptive voltage and timer-based load shedding schemes in a DC microgrid were compared with the existing conventional voltage based, timer-based and combined-based schemes under same disturbances. The study shows that the conventional schemes leads to larger voltage drop, voltage sags and causes unnecessary load shedding. The adaptive schemes utilizes ROCOV to achieve more

TABLE I: Summary of all Load Shedding Schemes

Scheme	**Trip Time CB1 (s)**	**Trip Time CB2 (s)**	**Trip Time CB3 (s)**	**V_{min} (V)**
Voltage Based	1.542	1.583	2.012	675
Timer Based	1.531	1.582	1.593	685
Combined Based	1.517	1.562	1.582	675
Adaptive Voltage Based	1.515	1.533	1.533	690
Adaptive Time Based	1.519	1.665	-	685

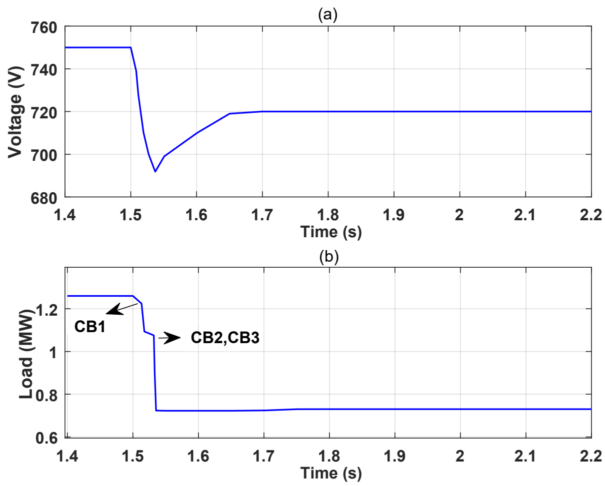

Fig. 9: Performance of Adaptive Voltage based scheme: **a)** DC Voltage **b)** Load power

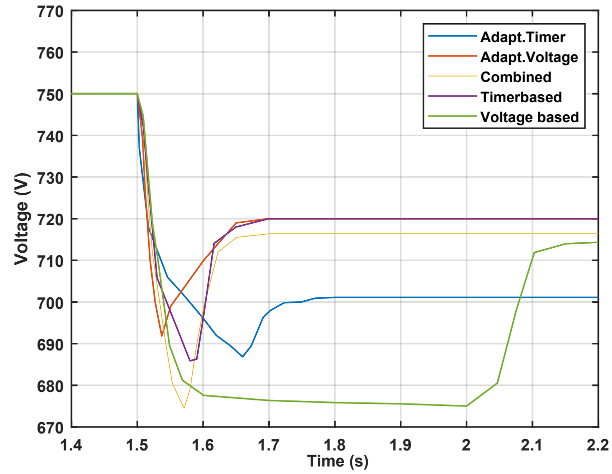

Fig. 11: Voltage Comparison of load shedding schemes

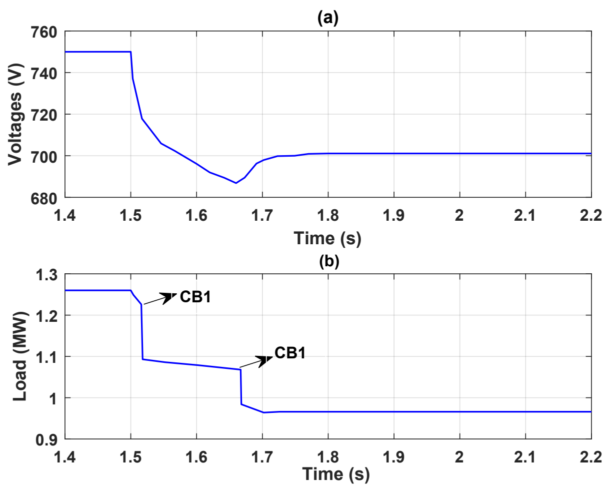

Fig. 10: Performance of Adaptive Timer based scheme: **a)** DC Voltage **b)** Load power

reliable assessment of the power imbalance thereby reducing the voltage drops and sags. The adaptive voltage scheme on the other hand exposes the critical loads to low voltage due to the utilization lower voltage threshold to shed loads with lower priorities, therefore it suitable for microgrid with small number of steps. The adaptive timer based tries to reduce the number of steps by utilizing longer time delays thereby exposing the critical loads to lower voltage. This work therefore leads to the need for more advanced load shedding schemes that can shed load optimally for future DC microgrids.

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