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Keywords

Distribution of electrical energy, Energy system management, Microgrids, Renewable energy systems; Smart grids

Abstract

Environmental concerns have led to increased penetration of renewable energy sources into the power grid. Many researches have considered localized and small-scale renewable energy sources supplying microgrids—small-scale localized distribution networks—as a backup to the main grid. Further, the aging of traditional transmission networks has led some researchers to propose islanded operations of the microgrid; the grid is isolated from the main grid and operates independently. However, islanded operations face many challenges such as power quality, voltage regulation, network stability, and protection. Moreover, renewable energy sources are unreliable and intermittent. Recent developments in power electronics have made it possible to develop competitive and reliable low-voltage DC (LVDC) distribution networks. Further, advances in information and communications technology (ICT) have led to smart grids in which various devices in the network can communicate with each other and/or a control center. In this paper, we consider an islanded LVDC smart microgrid that uses renewable energy sources. An energy management system (EMS) that ensures efficient energy and power balancing and voltage regulation is proposed for the network. The DC network utilizes solar panels for electricity production and lead-acid batteries as energy storage to support the production. The EMS uses the master/slave method with robust communication infrastructure to control the production, storage, and loads. The logical basis for the EMS operations has been established by proposing functionalities for the network components and defining operation modes that encompass all situations. During loss-of-power-supply periods, load prioritizations and disconnections are used to maintain power supply to at least some loads. The successful performance of the proposed EMS to maintain energy balance in the network has been demonstrated by simulations.

Introduction

Today, we have become increasingly reliant on electric power supply to sustain our economies, daily necessities, as well as comforts. However, the supply of uninterrupted electric power remains a challenging problem across the world, especially with increasing consumption and demand. Outages occur in many parts of the world, and the effects on customers are often severe. More reliable network solutions than the traditional 3-phase AC distribution systems are required. The aging of the current AC distribution grids, as well as their sizes and complexity, have also increased concerns about the reliable transmission and supply of electric power, especially across long distances to remote places. In this scenario, DC distribution has been proposed as a viable alternative, especially at low voltages.

Technical and economic developments during the last decade, especially in power electronics technology, have given the opportunity to develop competitive distribution systems based on low-voltage DC (LVDC) distributions [1]. At low voltages, the LVDC system is an economically feasible alternative that can enhance the reliability and energy efficiency of distribution systems as well as the power quality experienced by the customers. Further, small-scale power generation systems called distributed generations (DGs) can be connected to the LVDC distribution network [2]. It is now possible to connect small-scale DGs and energy storage devices to LV 1.5-kV DC networks [3].

LVDC distribution networks are an especially viable option for microgrids that can be used to supply smaller areas such as remote villages or buildings at low voltages. Microgrids are a localized grouping of electricity production equipment, energy storage devices, and loads, with the ability to function autonomously and co-cooperatively [4]–[5]. Microgrids generally use small energy sources—microsources—placed at customer sites and interfaced with the help of power electronics devices. Power electronics technologies provide the control and flexibility required by the microgrids concept [4]; power electronics interfaces have the disadvantage that they may increase harmonic injections and they can be sensitive to system disturbances, but this is not problematic in DC grids [6]. Microgrids using DGs decrease power failures caused by long-distance transmission grids [7].

Island networks are completely isolated from the main grid and operate completely independently and co-operatively. Islanded operations lead to various economic and technical issues such as power quality, voltage regulation, network stability, harmonics, reliability, protection, and control; hence, the system network must be extremely well planned. Modern electric grids have begun to use information and communications technology (ICT) systems to collect power supply and load demand information, perform relevant operations, and send control signals automatically in order to improve the efficiency, reliability, economics, and sustainability of the network; such grids are commonly referred to as smart grids. Real-time load information is recorded by “smart” meters and communicated by ICT systems to a control centre. Electric grids equipped with ICT systems are typically referred to as smart grids, and they are designed to respond automatically, quickly, and efficiently to power supply challenges [8].

This paper is based on the idea that LVDC islanded smart grids can be used to supply renewable-energy-based pollution-free electric power to isolated or remote locations with small loads, e.g., remote villages where cost-efficient and reliable electric supply can improve the quality of human life. In this study, an islanded smart bipolar LVDC microgrid network comprising solar energy and batteries has been considered. The radial network over a populated area (200 customers) has a diameter of approximately 6 km. On the basis of the European Union directive 2006/95/EC [22] and cable standardization, the nominal voltage of the bipolar network in this network is 750 V. Figure 1 shows an example of an LVDC distribution network over an area. Here, the topology is highly simplified.

An energy management system (EMS) is a system of computer-aided tools and operations used to monitor, control, and optimize the production and/or transmission efficiencies and overall network performances [9]. The EMS is facilitated by a robust communication infrastructure that regularly communicates the network system and component statuses, thereby enabling the software to perform the appropriate control operations. This paper presents a preliminary solution for the issues of energy balancing in the network by proposing an energy management system (EMS).

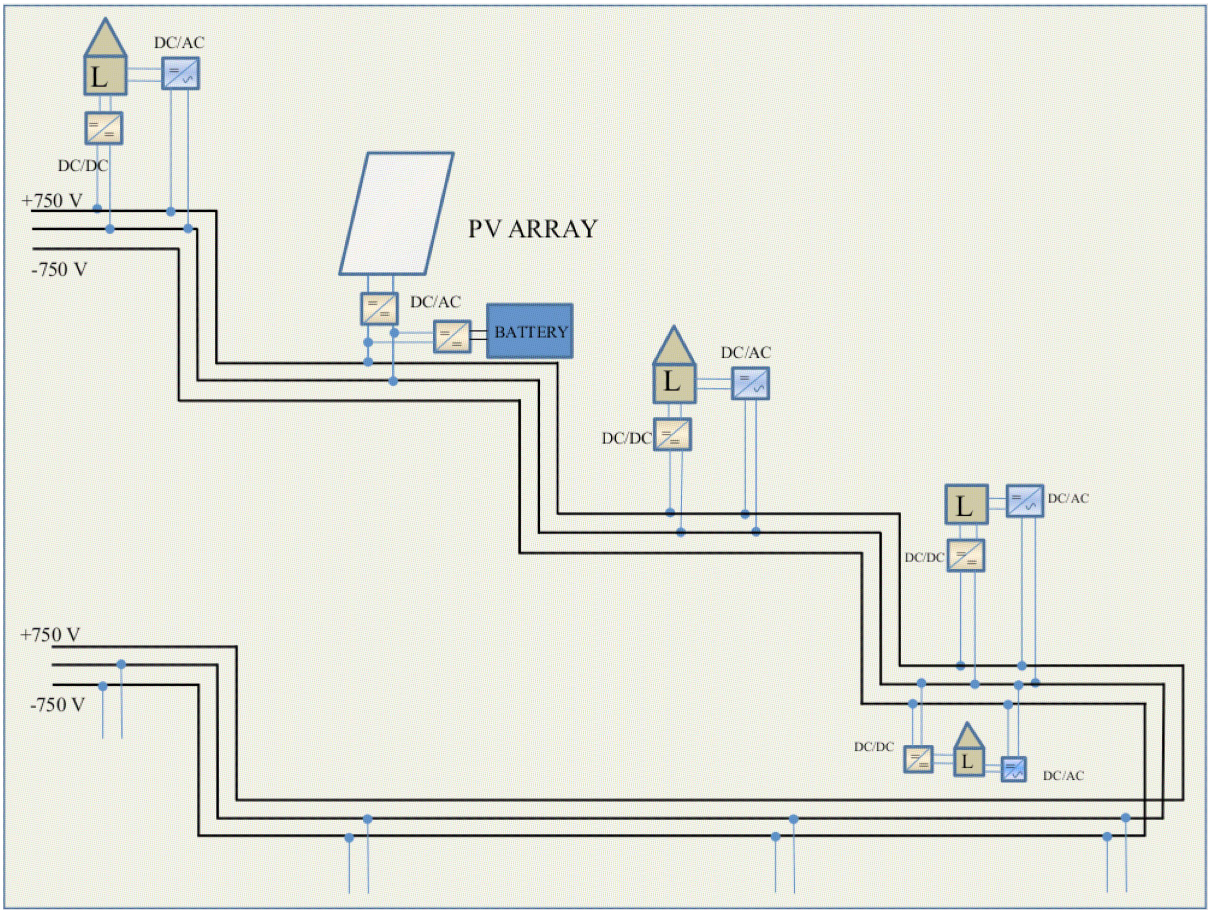

Fig. 1: Example of an LVDC distribution network over an area (with simplified topology); a PV array supplies power to randomly distributed loads, while a battery bank is used as backup. In practice, the loads would be distributed more unevenly and the cables would be more circuitous.

It is challenging to develop such an EMS for islanded LVDC networks because of production unreliability, battery charging, and load demands. The development of efficient and optimal EMSs for many kinds of networks has been discussed extensively in previous papers, and several approaches have been proposed. However, most of the published literature so far have focused on AC grid-connected microgrids wherein islanding operations have been typically considered as an alternative for deploying during emergencies or for any other specific requirements. Researchers have also considered many types of power production combinations such as PV–windpower AC microgrids, semi-autonomous microgrids, and hybrid AC–DC systems.

Bo et al. [10] introduced several strategies to maintain the power balance among renewable microsources, storage systems, loads, and the utility grid during grid-connected, islanded, and transition operations; their strategies involved the controlling of the different converters present in a microgrid comprising wind turbines, PV panels, and batteries. A three-phase inverter was used to maintain steady DC bus voltages during grid-connected operations, whereas microsources and storage systems were used in islanded operations; the magnitude and frequency of the AC bus were controlled by the droop character of parallel inverters. The droop control method has been the most frequently used technique in standalone AC microgrids for voltage and frequency control and has been analyzed many times [11]–[13]. Droop control essentially refers to active and reactive power regulation, and it is a decentralized control strategy wherein the active power output is adjusted according to the frequency deviation, and the reactive power output is adjusted based on the voltage deviation [14]. In [15], the feasibility of control strategies to be adopted for the operation of a microgrid when it becomes isolated was evaluated; in particular, the need for storage devices and load shedding strategies was considered.

A few researches have considered the grid-connected DC microgrid. Fuzzy control has also been proposed as a control method for DC microgrid systems. Chen at al. [16] presented fuzzy control to optimize the energy distribution in a DC microgrid comprising solar and wind power production, lithium-ion battery, DC load, and AC/DC converters; fuzzy logic was used to establish the control rules and to vary the battery state of charge (SOC) parameters. In a similar fashion, Papadimitriou and Vovos [17] proposed a fuzzy-based local controller for DGs that are either integrated into or isolated from the main network, depending on the requirements. Kakigano et al. [18] adopted a gain-scheduling technique on the basis is that it is difficult to achieve good voltage regulation and good load sharing when the DC voltage is controlled by several converters. Their technique changes the DC gain according to the output power in order to obtain better voltage regulation and load sharing simultaneously. Zhang et al. [19] proposed the power control of DC microgrids using DC bus signalling; the DC bus voltage level was employed as an information carrier to distinguish four different operation modes. The power was controlled by controlling the modular PV converters, battery converters, and grid-connected converters, and smooth switching was realized between constant voltage operations and maximum power point tracking (MPPT) operations. Even though their study basically involved grid-connected networks, the proposed control method maintained the power balance of the DC microgrid even when islanded.

Few researches have been conducted into the development of an EMS for such completely islanded LVDC microgrids whose power production is based on renewable (hence, variable) energy. Karlsson and Svensson [20] suggested two methods for achieving power balance control in such networks: the communication or master/slave method, which relies on fast communication between the source and load converters, and droop control which does not require any communication at all. In Liao and Ruan [21], a power management control strategy has been proposed for a stand-alone photovoltaic (PV) power system comprising PV array, battery, and DC–DC converters. Their power management control strategy was to control the converters to operate in suitable modes according to the PV power and battery statuses. However, their strategy is applicable only to small loads and does not cover all the possibilities that can occur when numerous customers have to be supplied power reliably. Moreover, they have not considered emergency situations wherein there is insufficient or no power production.

The EMS proposed in this paper employs several tools to achieve energy balance, such as load shedding, production control, and battery state of charge (SOC) control. Operation modes that encompass all conditions have been derived, analyzed, and used as the basis for the EMS operations. The master/slave method is used with robust communication infrastructure and modern power electronics interfaces. The proposed EMS consists of a control algorithm that ensures optimal power balance in the network and elicits quick responses to emergencies. Load prioritization and disconnection are employed to ensure that some loads continue to receive power supply, even when there are power production issues. The existence of high-speed and reliable ICT infrastructure has been assumed. All the algorithms were implemented using MATLAB©, and all the simulations were also performed using MATLAB©.

This paper is organized as follows. First, the power-system operation functionalities and modes that encompass the various situations faced by an LVDC island network are enumerated and described. Subsequently, the power balance methodology is explained. The results of the simulation and discussions are presented subsequently. Finally, the main results of the paper are summarized, and future research areas are elucidated.

Functionalities of Network Components

Energy balancing requires the inputs and outputs of the PV array, battery, and load to be analyzed and controlled. In DC networks, the PV array always *supplies* power, while the load always *absorbs* power; in contrast, the battery both *supplies* as well as absorbs power. Further, the power outputs from the PV array and battery and the power input into the battery are controllable, while the load power demand can only be adjusted by disconnection based on prioritization.

This paper proposes power-system operation modes that encompass the various situations faced by an LVDC island network and considers power and energy management strategies for all possible scenarios. The PV array, battery bank, and load have different operation modes depending on the network conditions (normal operations or emergency operations). The control algorithm is designed to send control signals based on this logical foundation.

PV array

The operating modes of the PV array are as follows:

(1) *Load Supply Mode*: The PV array, in combination with the MPPT algorithm, produces as much power as possible and is able to meet all the loads;
(2) *Limited Load Supply Mode*: The PV array, in combination with the MPPT algorithm, produces as much power as possible but the power supply is not sufficient to meet all the loads;
(3) *Constrained Mode*: In this mode, the PV array is constrained to output less power than the maximum power from the MPPT in order to balance power or energy;
(4) *Switchoff Mode*: PV array is switched off and there is no power production from the PV array.

Battery

The SOC is practically the most important parameter in network control, and battery charges and discharges are primarily used for the control. Three SOC limits have been defined: maximum SOC limit, SOC_{max}, minimum SOC limit, SOC_{min}, and lowest possible SOC, SOC_{least}. Control signals are sent to the battery based on the decision taken by the algorithm, and the battery enters one of the following operation modes:

(1) *Charge Mode*: Battery charged at the maximum charge rate;
(2) *Limited Charge Mode*: Battery is charged, but not fully;
(3) *Discharge Mode*: Battery is discharged at the maximum discharge rate;
(4) *Limited Discharge Mode*: Battery is discharged, but not fully;
(5) *SwitchOff Mode*: Battery is switched off and neither charging nor discharging takes place.

Load division and prioritization

Since it is not always possible to meet the load demand, load prioritization, load disconnection, and load shedding are potential solutions. This study proposes to divide the loads into three categories with certain priorities and further sub-divided into sub-loads with sub-priorities. The loads are then considered to have different operation modes that depend on whether the total load demand can be met or not and the consequent prioritization. The operation modes, load categories, and prioritization are as follows.

(1) *Normal Load Operations*: All the loads receive power supply without any constraint.
(2) *Load-Constrained Operations*: Only some loads can be serviced. The choice of the loads that can be serviced is based on the load category and their prioritization, and this determines the operation mode as well.
    (a) Critical-Loads Mode: In this mode, only the critical loads are supplied. Critical loads are the most vital loads in the network, whose servicing may be a life-and-death issue. Examples of critical loads are hospitals (or, doctors' clinics), critical lighting (highways or bus stations), emergency services, triage centres, and disaster-response areas.
    (b) Essential-Loads Mode: Only essential loads are supplied in this mode. Essential loads refer to loads that are not vital, but, nevertheless, are important. Typical examples of such loads are banks, ATMs, street lighting, schools, houses, and water-pumping

stations. Critical loads are typically community loads, but essential loads can also be household loads such as lighting.
(c) Normal-Loads Mode: Normal loads refer to any other loads besides critical and essential loads. Typically, these loads may be household loads such as fans, refrigeration, internet, and television.

In addition, all the loads may or may not have sub-loads, which implies that there is a need for internal prioritization. To illustrate this, consider Critical Loads. First of all, there may be many critical loads with different criticalities; hospitals or medical services, for example, may be more critical than lighting loads. Hence, each load type has a "sub-Load Mode" which is referred to as Limited Critical/Essential/Normal Load Mode when all the loads belonging to that load type cannot be serviced. Moreover, each critical load may or may not have several loads. For example, hospitals/doctors' clinics may have several loads of varying importance (intensive care units are more critical than a waiting room!), whereas, in contrast, lighting loads could be grouped as one load that does not need any further sub-divisions. Figure 2 illustrates this mechanism. Top-level loads refer to the three main loads—critical, essential, and normal—and sub-loads refer to loads such as street lighting or households or hospitals, and super-sub-loads are the smallest loads such as fans, intensive care units, or refrigerators. Some super-sub-loads may be independent, for example, power supplies for communication devices or a transformer (if required).

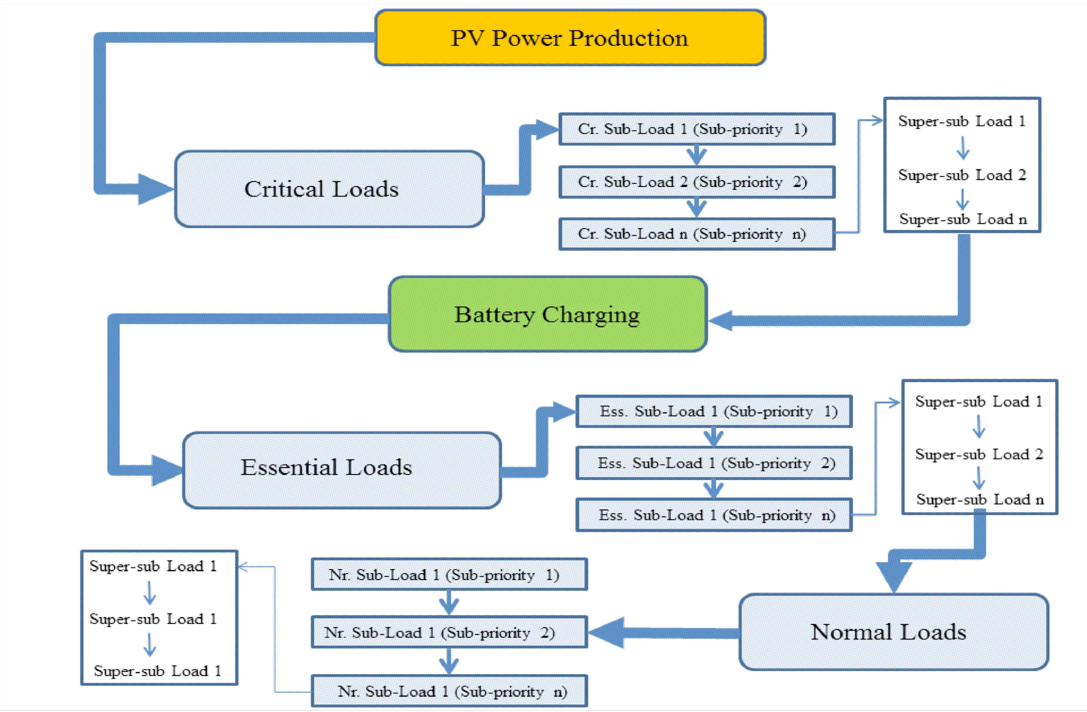

Fig. 2: Load prioritization flow

Finally, each and every individual load prioritization must be input into the EMS before the operations begin. Typically, this should be done by the network operator on the basis of customer requirements, location-related issues, and technical or other constraints.

Power Balance Methodology

In the island LVDC network, power balancing is performed at regular time intervals by collecting production, storage, and consumption data and making the appropriate decisions. To perform these controls, two types of operations have been defined depending on the status of the network: **Normal** and **Subnormal** operations.

Normal Operations

Normal operations refer to the network control setting when the power production and storage statuses are ideal—either the appropriately sized PV array, the battery, or both together are capable of supplying the loads. In the ideal case, the PV array can not only meet the load demand but also the battery charging requirements, if any, whereas, in the non-ideal case, the battery assists the PV array to meet the load demand, being allowed to discharge until the minimum limit. The battery SOC is required to remain in the following range: Minimum SOC ≤ Battery SOC ≤ Maximum SOC

Further, on the basis of the PV power production status, two operation modes have been defined—*Optimal-Operation Mode* and *Sub-Optimal-Operation Mode*—in this study as follows:

> 1. *Optimal-Operation Mode*: PV production alone is sufficient to meet the load demand AND to charge the battery completely.
> 2. *Sub-Optimal-Operation Mode*: PV production alone is not sufficient to meet the load demand AND to charge battery completely (if required). Note that, nevertheless, PV production + battery discharge is sufficient to meet the load demand and, maybe, to at least partially charge the battery.

In both these modes, the statuses from the various parts of the network are checked and the conditions are checked, and the status recorded by the algorithm. The network components are then considered to be in one of the designated modes; for example, consider the Optimal-Operation Mode. When the Battery SOC is at its maximum limit, the PV array goes into Load Supply Mode and the battery goes into SwitchOff Mode. Similarly, consider the case when the network is in the *Sub-Optimal-Operation Mode*. When there is some PV production and it is sufficient to meet load demand but not to charge battery completely: the PV array goes into Load Supply Mode and battery goes into Limited Charge Mode. The algorithm uses the status indicator, and performs the required actions that correspond to the particular mode.

Sub-Normal Operations

The network is considered to be operating in the Subnormal setting either when the total load demand is not met, or if the battery is forced to cycle deeper than normal, that is, SOC ≤ Minimum SOC. This can happen for a variety of reasons: neither the PV array nor the battery, singly or in combination, may be able to supply all the loads; or the network or power production may be disrupted in some manner; or the battery may have been cycled for too long in the previous time periods. During subnormal operations, typically, the PV power production is zero (night) or insignificant (dawn or dusk or cloud cover); the battery SOC is too low; or, the battery's discharge rate is too small to meet the load demand in that time period. In addition, such situations can occur even when the PV power production and battery SOC are high, if the load demand is abnormally high, although this would mostly be a consequence of poor sizing.

If the above-mentioned conditions for normal operations are not met, the EMS reverts the network operations to subnormal setting. The battery SOC will now remain in the following range: Least Possible SOC ≤ Battery SOC ≤ Maximum SOC.

Unlike the case of normal operations, both the PV production and battery SOC statuses are used to define the two operation modes—Optimal-Operation Mode and Sub-Optimal-Operation Mode.

> 1. *Optimal-Operation Mode*: PV array and battery, singly or together, can meet the total load demand, but only if battery is cycled to below the minimum limit to the least possible limit; hence, Least Possible SOC ≤ Battery SOC ≤ Minimum SOC.
> 2. *Emergency-Operation Mode*: PV array and battery, singly or together, cannot meet the total load demand, even if battery is cycled deeply, and some loads have to be disconnected. Least Possible SOC ≤ Battery SOC ≤ Maximum SOC.

As in the case of normal operations, both these modes have several scenarios and actions that depend on certain conditions. For example, in the Optimal-Operation Mode (Subnormal), when there is no PV production: the PV array goes into Switchoff Mode and battery goes into Discharge Mode. In the Emergency-Operation Mode (Subnormal), load disconnection and prioritization is a key feature. The EMS checks the statuses and, for example, when in the Critical-Battery Load (CB) Mode, all critical loads can be supplied power, and if SOC < SOC_{min}, battery is charged preferentially over supplying essential loads (in accordance with the prioritization scheme given earlier).

Results and Discussion

The algorithm was written and implemented in Matlab based on the above-mentioned methodology. The simulations were conducted using the following data. The total number of customer connections = 20; this was divided into 1 Critical Load, 8 Essential Loads, and 11 Normal Loads. The peak power of the customers = 800 W. The load profile was taken from a Finnish customer's load profile. The solar irradiation data was taken for 60° latitude using the SoDa service. Other input parameters were typical parameters (e.g., Least Possible SOC = 50%). High battery and solar array values were used to verify normal operations. They were then reduced to verify emergency operations: the battery capacity was reduced to 300 Ah (225 kW h) and the PV array size was reduced to 300 kW. Figure 2 shows the results for emergency operations. The algorithm clearly performs efficiently and allocates resources according to the prioritization.

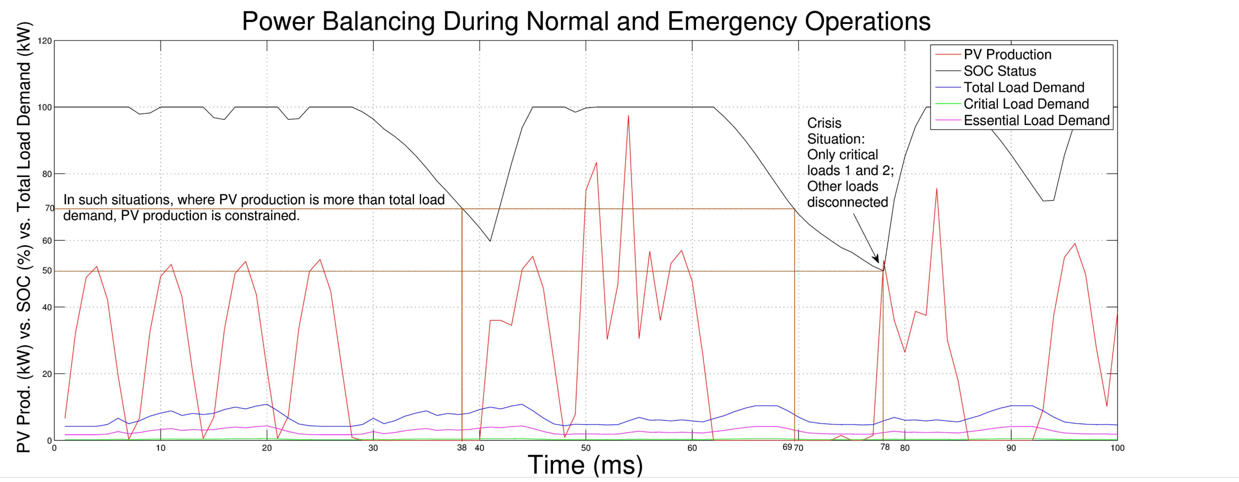

Fig. 3: Power balancing under normal and subnormal conditions

The proposed paradigm and EMS are fairly basic approaches and represent initial ideas into the development of LVDC islanded microgrids. The proposed algorithm is somewhat simplistic, and considerably more work is required to improve its intelligence, efficiency, and robustness. Although the algorithm does solve the problems of energy balancing with a simple approach, more research is required to improve the control of the converters and battery storage. In particular, it is critical to consider the impact of current and voltage and the stability issues of the converter interaction, which would be significant in the time scale. Additionally, the prioritization is based on user inputs, which may not always be convenient or desirable. A clever reinforcement learning algorithm that learns the prioritization may represent a considerable improvement. Alternatively, a market-based exchange of price to determine the prioritization can be considered. Further, the model is based on a trial microgrid, and its actual implementation is pending. Responses to challenges during an actual implementation and the results remain pending studies.

Conclusions

In this paper, an LVDC islanded 750-V bipolar network using renewable energy sources has been considered for applications in remote locations that have low or no power supplies; renewable energy sources are proposed for energy generation and battery backup is considered. A PV array is considered for supplying power to typical domestic customer loads that can be flexible and prioritized, and lead-acid batteries are used. The battery bank is connected to the LVDC bus with DC/DC converters, and it incorporates a management system that communicates the current battery statuses reliably and quickly, while also being able to accept control instructions and perform the required actions. Both DC/AC and DC/DC load converters regularly communicate all relevant information from the loads to the control algorithm.

A simple EMS to control the power and energy balancing of the network has been designed. The proposed EMS is based on the master-slave/communication approach that relies on robust ICT infrastructure. The principles of EMS operations were logically established by defining functionalities and operation modes of the network elements, which encompass all possible supply, storage, and load combinations under all conditions. The EMS efficiency was verified and demonstrated by conducting simulations with a section of the entire network; the EMS successfully and efficiently performed both energy balancing and voltage regulation. However, considerable improvements are still required in order to improve the efficiency and intelligence of the control.

Completely islanded microgrids can be employed to supply renewable-energy-based pollution-free electric power to isolated or remote locations comprising small loads, such as remote villages that have never received electric power supply. By using such completely islanded microgrids, such places can be supplied electricity in a cost-efficient and effective manner; this has important social benefits since the quality of human life will be improved. This paper has taken a small but important step toward “replacing the candle” in villages by developing an efficient and robust EMS for LVDC networks.

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