

Dynamical modelling of a DC microgrid using a port-Hamiltonian formalism

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Abstract: This paper presents the dynamical model of a DC microgrid, composed by a solar panel, an energy storage system, a utility grid and a group of interconnected loads, such as housing-office equipment and electrical vehicles. The transmission lines connect the energy sources with the loads through the corresponding switching DC/DC converters. The novelty resides in the port-Hamiltonian formulations developed for the physical model which is first described through a Bond Graph. An extended architecture of the system with a meshed topology is presented. The proposed architecture has the ability to reduce the power losses within the DC microgrid system by increasing the different transmission line paths among the sources and the loads. The global dynamical model of the system is finally converted into a state-space representation. Furthermore, in view of system control and optimization we formulate the load balancing problem of the DC microgrid in order to stabilize the power flow within the DC bus. The model is validated with some primary simulations.

Keywords: Bond graph, port-Hamiltonian formulation, meshed DC microgrid, load balancing.

1. INTRODUCTION

Over the past few years, the increasing demand on energy usage and generation in buildings (residential, commercial, industrial) requires flexibility and efficiency of the energy consumption. The main grid cannot offer energy independence and does not ensure the continuity and the reliability of the power transmission. This is where the notion of microgrids enters the picture. Lately, the interest on DC microgrids tends to increase as a result of the continuous development and production of the DC equipment, such as solar panels (PV), electrical vehicles (EV), LED lights and batteries. Furthermore, the meshed DC microgrid can provide greater reliability since the electricity can be transmitted through a variety of sources and paths (Guerrero et al., 2013). The division of a system into many autonomous subsystems allows a collaborative communication among them, a factor that maximizes the system's performance.

In DC microgrids, the development of a control method is required in order to optimize the energy distribution within the system. Therefore, the establishment of accurate mathematical models plays a crucial role. Nevertheless, the analysis of such models gets complicated because of the large amount of factors and components that are taken into account (Gu et al., 2014). For this reason, the researchers have focused on producing suitable models separately for each unit of the system. Several models of distributed energy resources (DERs) have been already proposed in the literature, like for the PVs. Moreover, the

energy storage system (ES) is indispensable for minimizing the system's failures. Over the years, several models of different kind of batteries have been proposed and can be divided into two categories, the electrochemical model (Smith et al., 2010) and the electrical circuit model (Manwell and McGowan, 1993).

We underline that the analysis of the model of the DC/DC converters used for the transmission lines' interconnection within the DC bus is of high importance. The most common mathematical approach is the switching model that describes the electrical circuits' operation. Next, the averaged modelling of the converters neglects the fast switching by changing the switching interval (Chiniforoosh et al., 2010). Another important aspect in a microgrid system is the load modelling, for which the researchers use profiles that are based on either a physical process (Gu et al., 2014) or data analysis on consumption in a residential or industrial environment without considering in detail the internal process of the system (Khodaei, 2014). Furthermore, from a topological viewpoint, the meshed DC microgrid modelling and control is still of high interest for both industrial and academic applications due to its advantageous structure with numerous transmission lines and paths, that encourages possible faults mitigation.

In the present work, we present a meshed DC microgrid with its dynamical equations. We use the notion of the Bond Graph and their associated port-Hamiltonian formulation (van der Schaft and Jeltsema, 2014), this being a method ideally suited for the description of the energetic parts of a multi-physical system as a DC microgrid (Ortega et al., 2008). This modelling approach will further facilitate

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the integration of control and optimization for solving the energy management problem within the system. The contributions of this paper are listed below:

- presentation of a DC microgrid with meshed topology;
- dynamical modelling with the Bond Graph representation and its associated port-Hamiltonian formulation for each component of the DC microgrid;
- insights on the load balancing problem.

The work presented below is organized as follows. Section 2 refers to the modelling methodology of the proposed model. Section 3 describes a preliminary load balancing formulation for the system. In Section 4, we draw the conclusions and give insights on the future work.

2. DC MICROGRID MODELLING

This section presents the modelling methodology adopted for the meshed DC microgrid system which will be globally represented as an RLC electrical circuit.

2.1 Modelling methodology

The dynamics of the system is presented based on the Bond Graph and their port-Hamiltonian representations (van der Schaft and Jeltsema, 2014). The Bond Graph represents a multiport physical system based on energy exchange and is regarded as the interconnection of three types of components: the energy-source elements, the energy-storing elements and the energy dissipating elements. The derived equations, generated from the Bond Graph, are in the form of a port-Hamiltonian system (PH), generally described by:

$$\begin{aligned}\dot{x} &= [J - R]Qx - Gu, \\ y &= G^T Qx + Du,\end{aligned}\quad (1)$$

where $x \in R^n$ is the matrix of states composed by p and q which are the displacement variables that denote for an RLC circuit the magnetic flux of the inductors and the charge of the capacitors correspondingly, $u \in R^m$ is the input vector of the system, $y \in R^m$ is the output vector, $J \in R^{n \times n}$ is a skew-symmetric matrix, $R \in R^{n \times n}$ is the matrix of dissipating elements, $G \in R^{n \times m}$ is called the input matrix, Q is a diagonal matrix of all the circuit parameters and D is a matrix depending on the port variables with appropriate dimensions (Escobar et al., 2015).

The storage function of the system is called the Hamiltonian, which describes the total energy and is equal to:

$$H(x) = \frac{1}{2}x^T Qx. \quad (2)$$

Next, the components of the microgrid will be modelled using the above formalism.

2.2 Model of the meshed DC microgrid

The meshed DC microgrid considered in this work (see Fig. 1) is composed by a renewable energy source (PV), an electrical storage (ES) composed by lead-acid batteries and an amount of loads (office and housing devices, EVs). The microgrid is connected to a three-phase utility grid (UG) and with the PV, they constitute the main power sources

of the system. Between the UG and the DC microgrid, there is a DC breaker. When the DC breaker switch is open, the DC microgrid is disconnected from the AC-grid and operates autonomously in islanded mode.

The most significant part of the system are the switching DC/DC converters, considering that they are the main components capable of controlling the power flow and direction within the DC bus. The DC/DC converters used for the system are of two types. Primarily, we have a type of bi-directional buck-boost converter, called the Split-Pi converter, which can produce an output voltage higher or lower than the input voltage. Additionally, it consists of four switches, a necessary element for the bidirectional voltage regulation. A pair of Split-Pi converters forms the smart node (SN) which takes decisions related to the energy demand, the energy cost, the load balancing and the state of charge of the ES. Secondly, we have an unidirectional buck-boost converter, called the Ćuk converter (Escobar et al., 2015). This converter will be used for the regulation of the loads' input voltage. The converters' switch is characterized by each duty cycle d defining the converter's activity over a period of time.

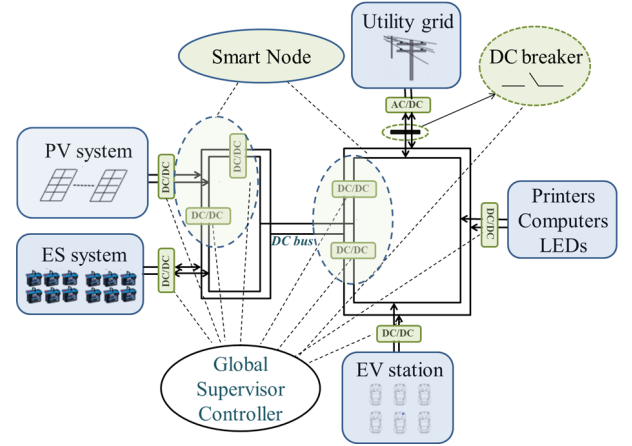


Fig. 1. Meshed DC microgrid architecture.

In the sequel we present the Bond graph (Fig. 2) of the proposed meshed DC microgrid. The three meshes represented in Fig. 1 and Fig. 2 are:

- a collection of solar panels connected with the lead-acid batteries for the microgrid's energy generation;
- an EV station;
- various loads (printers, computers, LED lighting, mobile phones and the like).

Concerning the loads' and EVs' network, they are composed by a certain number of nodes, each one corresponding to a load and they are linked together with the transmission lines. The transmission lines are considered as a resistor and an inductor in series, a structure that encourages the reliability of the transmission network.

2.3 Model of the PV solar cell

The PV system is composed by a collection of solar cells in parallel and in series. The solar cell is an electrical device that collects the solar irradiation and generates electricity. The equivalent circuit is shown in Fig. 3 with its Bond Graph. Notice that we do not have any storing elements

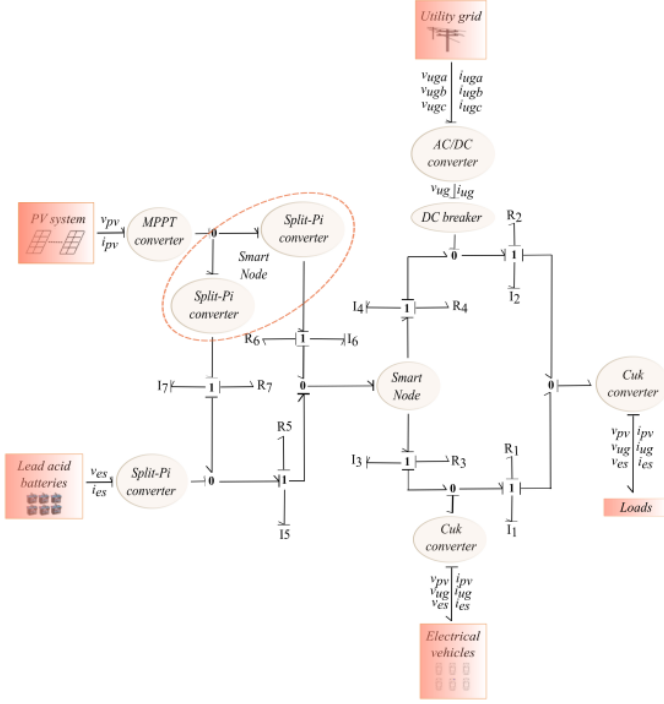


Fig. 2. Bond Graph of the meshed DC microgrid.

shown in the graph, thus the power conservation property reduces to the following equation:

$$v_S i_S + v_D i_D + v_{R_{sh}} i_{R_{sh}} + v_{R_s} i_{R_s} + v_R i_R = 0, \quad (3)$$

where S is the sunlight source, R_s is the resistance in series, R_{sh} is the shunt resistance of the system, D is the diode and R refers to the load of the system. In addition, we can obtain from the 0/1 junctions the following:

$$\begin{aligned} i_S &= i_D + i_{R_{sh}} + i_{R_s}, \\ v_{R_s} &= v_D - v_R. \end{aligned} \quad (4)$$

The output of the system is the current i_R and the voltage v_R of the solar cell and gathers its output power. All the other unknown variables of (3) and (4) exist in the literature and they are calculated based on the PV characteristics and type. For testing the presented PV model we consider a DS-100 MPV module with an input solar irradiation equal to $800W/m^2$ and an external temperature equal to $25^\circ C$ and represent in Fig. 4 the I-V curve and the P-V curve.

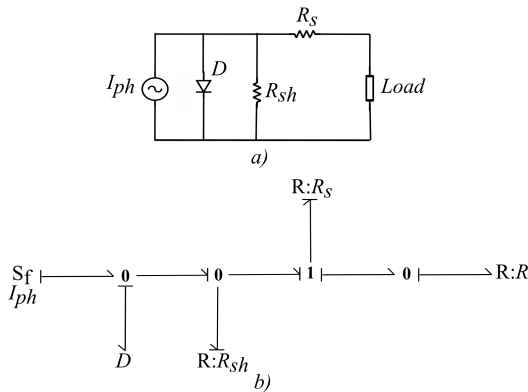


Fig. 3. a) PV cell's circuit. b) Corresponding Bond Graph.

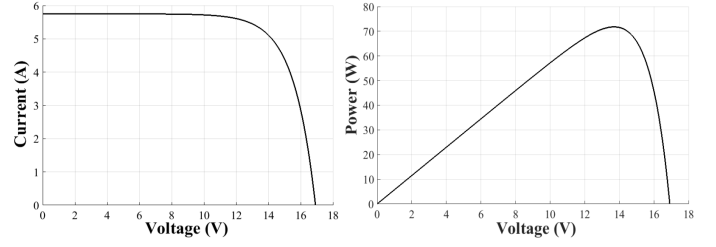


Fig. 4. $I - V$ and $P - V$ curves of the PV model.

2.4 Model of the lead-acid battery

Hereinafter, we present the description of the lead-acid battery PH model. In this work we consider a Kinetic Battery Model (KiBaM) (Manwell and McGowan, 1993) which is described by a first order approximation. Fig. 5a illustrates a two-tank model, the bound charge and the available charge, separated by a conductance k_b . The tank q_{1b} supplies electrons directly to the load and the tank q_{2b} supplies electrons only to the available-charge tank. The flow between the tanks depends on the difference between $h_{2b} = \frac{q_{2b}}{1-c_b}$ and $h_{1b} = \frac{q_{1b}}{c_b}$ and on the parameter k_b . In Fig. 5b, we determine the Bond Graph during charging. We consider the two tanks as two storage elements and, between them as well as between the source and the first tank, we add a resistance in order to perform properly the causality property.

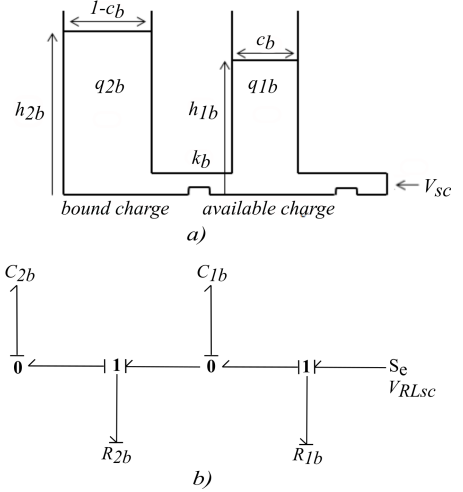


Fig. 5. a) KiBaM model, where c_b is the total capacity of the battery. b) Bond Graph of the KiBaM model during charging mode.

From the Bond Graph the associated PH model is derived as follows:

$$\begin{cases} \begin{bmatrix} \dot{q}_{1b} \\ \dot{q}_{2b} \end{bmatrix} = [J_b - R_b] Q_b x_b + \begin{bmatrix} -\frac{1}{R_{1b}} \\ 0 \end{bmatrix} (-v_{sc}), \\ i_{sc} = \begin{bmatrix} -\frac{1}{R_{1b}} & 0 \end{bmatrix} Q_b x_b + \begin{bmatrix} \frac{1}{R_{1b}} \end{bmatrix} v_{sc}, \end{cases} \quad (5)$$

where $x_b = [q_{1b} \ q_{2b}]^T \in R^{1 \times 2}$ is the state vector, $v_{sc} \in R$ is the system's input vector denoting the input voltage coming from the input voltage denoting the input voltage coming from the Split-Pi converter connected with the battery, $i_{sc} \in R$ is the output vector, where i_{sc} is the battery's current during charging. The dissipation matrix $R_b \in R^{2 \times 2}$ is equal to:

$$R_b = \begin{bmatrix} \frac{1}{R_{1b}} + \frac{1}{R_{2b}} & -\frac{1}{R_{2b}} \\ -\frac{1}{R_{2b}} & \frac{1}{R_{2b}} \end{bmatrix}. \quad (6)$$

All the unknown variables and parameters of the battery model can be found in the literature and depend on the type of the lead-acid battery that is used. The charging and discharging procedure of the battery will be controlled by the Split-Pi converter, presented in the next section. As presented before, the matrix J_b of the battery PH representation is equal to 0. By connecting the battery circuit to the Split-Pi converter, we are able to obtain the J matrix, that is important for the physical dynamics characterization. For illustration purpose we consider here an AGM 12-165 model of the battery and represent in Fig. 6 the available charge of the battery.

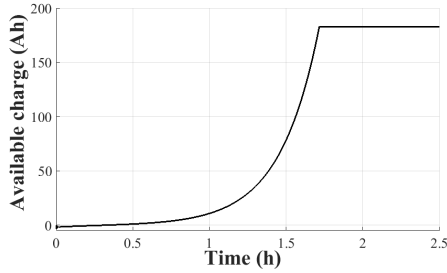


Fig. 6. Available charge of the battery, which is connected through the Split-Pi converter to the common bus (400V).

2.5 Model of the Split-Pi converter

Next we introduce the mathematical analysis of the Split-Pi converter of the system. We start by presenting in Fig. 7 the electrical circuit of the Split-Pi converter and its equivalent Bond Graph. In the Bond Graph, we add a resistor element after the source in order to ensure the causality property problem.

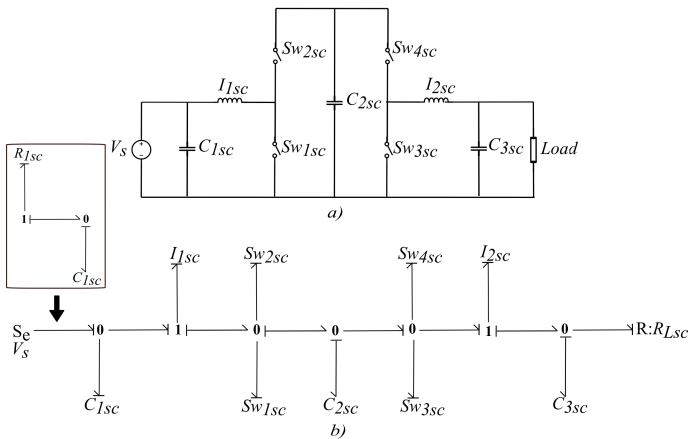


Fig. 7. a) Split-Pi converter electrical circuit. b) Corresponding Bond Graph.

According to the Bond Graph of the converter, we build its state-space representation:

$$\begin{cases} \begin{bmatrix} \dot{p}_{1sc} \\ \dot{p}_{2sc} \\ \dot{q}_{1sc} \\ \dot{q}_{2sc} \\ \dot{q}_{3sc} \end{bmatrix} = [J_{sc} - R_{sc}]Q_{sc}x_{sc} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\frac{1}{R_{1sc}} & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} u_{sc}, \\ \begin{bmatrix} i_S \\ v_{R_{1sc}} \\ v_{R_{Lsc}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{R_{1sc}} & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} Q_{sc}x_{sc} + \begin{bmatrix} \frac{1}{R_{1sc}} \\ 1 \\ 0 \end{bmatrix} v_S, \end{cases} \quad (7)$$

where $x_{sc} = [p_{1sc} \ p_{2sc} \ q_{1sc} \ q_{2sc} \ q_{3sc}]^T \in R^{1 \times 5}$ is the state vector, $u_{sc} = [-v_S \ i_{R_{1sc}} \ -i_{R_{Lsc}}]^T \in R^{1 \times 3}$ is the system's input represented by the input voltage v_S generated from the source, the PV or the ES, and by the current of the resistance R_{1sc} , $i_{R_{1sc}} = \frac{q_{1sc}}{R_{1sc}C_{1sc}}$, and the current of the load $i_{R_{Lsc}} = \frac{q_{3sc}}{R_{Lsc}C_{3sc}}$, $y_{sc} = [i_S \ v_{R_{Lsc}}]^T \in R^{1 \times 2}$ is the output vector, i_S is the current of the source and $v_{R_{Lsc}}$ is the output voltage of the converter. The dissipation matrix R_{sc} is equal to 0 and the matrix $J_{sc} \in R^{5 \times 5}$ is described below:

$$J_{sc} = \begin{bmatrix} 0 & 0 & 1 & -(1-d_{1sc}(t)) & 0 \\ 0 & 0 & 0 & d_{2sc}(t) & -1 \\ -1 & 0 & 0 & 0 & 0 \\ 1-d_{1sc}(t) & -d_{2sc}(t) & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \quad (8)$$

where values $d_{1sc}(t), d_{2sc}(t)$ are the control variables representing the duty cycles of the converter's switches. For the simulation depicted in Fig. 8 we consider that the input voltage is from the common DC bus which is equal to 400V and as an output we have a stable load with a resistance equal to $R_{Lsc} = 0.1\Omega$.

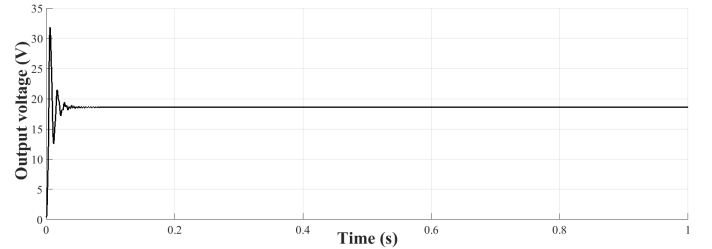


Fig. 8. Output voltage of the Split-Pi DC/DC converter.

2.6 Model of the Ćuk converter

In the following we present the Bond Graph and the corresponding PH representations of the Ćuk converter (see Fig. 9)(Escobar et al., 2015). From the representation in Fig. 9 we obtain the following state-space representation of the system:

$$\begin{cases} \begin{bmatrix} \dot{p}_{1cc} \\ \dot{p}_{2cc} \\ \dot{q}_{1cc} \\ \dot{q}_{2cc} \end{bmatrix} = [J_{cc} - R_{cc}]Q_{cc}x_{cc} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_S \\ -\frac{q_{2cc}}{R_{Lcc}C_{2cc}} \end{bmatrix}, \\ \begin{bmatrix} i_S \\ v_{R_{Lcc}} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} Q_{cc}x_{cc}, \end{cases} \quad (9)$$

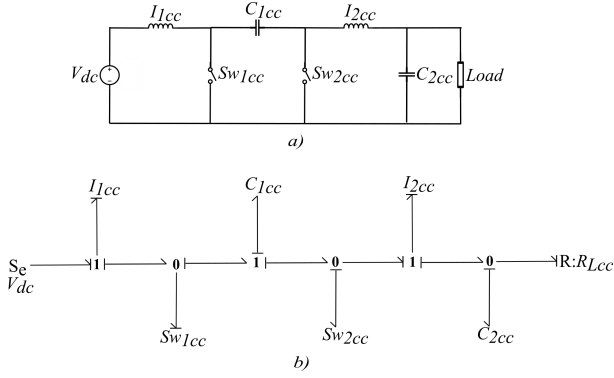


Fig. 9. a) Electrical circuit of the Ćuk converter. b) Corresponding Bond Graph.

where $x_{cc} = [p_{1cc} \ p_{2cc} \ q_{1cc} \ q_{2cc}]^T \in R^{1 \times 4}$ is the state vector, $u_{cc} = [v_S \ -\frac{q_{2cc}}{R_{Lcc}C_{2cc}}] \in R^{1 \times 2}$ is the system's input vector denoting the input voltage v_S from the DC bus and the load's current $i_{R_{Lcc}} = \frac{q_{2cc}}{R_{Lcc}C_{2cc}}$, $y_{cc} = [i_S \ v_{R_{Lcc}}]^T \in R^{1 \times 2}$ is the output vector, i_{dc} is the input current and $v_{R_{Lcc}}$ is the output voltage of the converter. The matrix R_{cc} is equal to 0 and $J_{sc} \in R^{4 \times 4}$ is represented below:

$$J_{cc} = \begin{bmatrix} 0 & 0 & -(1-d_{cc}(t)) & 0 \\ 0 & 0 & -d_{cc}(t) & -1 \\ 1-d_{cc}(t) & d_{cc}(t) & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (10)$$

The value $d_{cc}(t)$ is the control variable of the converter that corresponds to the two switches' activity. The Ćuk converter will regulate the input voltage of the loads, for which we will use a profile based on the consumer's demand. In Fig. 10 we present a simulation of the Ćuk converter output voltage for which we consider as input the common DC bus voltage equal to 400V and as output a stable load with a resistance equal to $R = 10\Omega$.

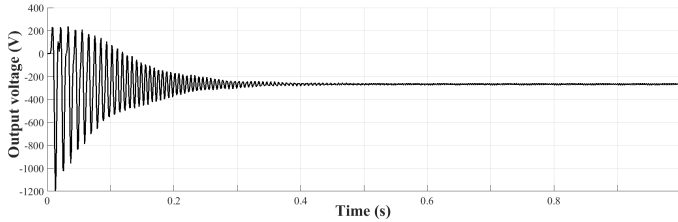


Fig. 10. Output voltage of the Ćuk converter.

3. LOAD BALANCING PROBLEM FORMULATION

The load balancing problem describes the regulation of the DC-voltage in multi-terminal DC networks, else called the optimal power flow problem among the transmission lines. The purpose of this procedure is to find the optimal working point of the system by using a set of constraints in power, current and voltage.

We consider the system in Fig. 1 as a set of four cyclic networks. A cyclic network is the result of the nodes' interconnection. Each node corresponds to a DER or a load. Furthermore, each node can be connected to another cyclic network. In this way, we can develop a meshed cyclic network, as it is presented in Fig.11, that consists of numerous power transmission lines.

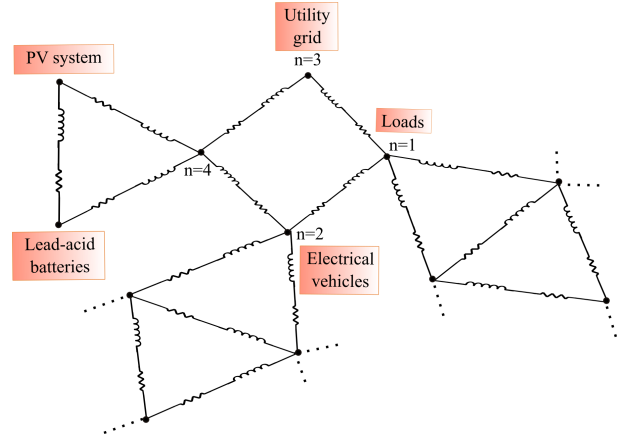


Fig. 11. The cyclic network of the proposed meshed DC microgrid.

In order to develop the load balancing problem, we will consider the part of the sources, the loads and the EVs as a node and we will focus, primarily, on the central network. The transmission network is represented as a circuit with storage and dissipative elements. The station of the EVs will be utilized as an ES system both for the DC microgrid and the EVs' charging. Thus, a Bond Graph is developed (see Fig.12), from which the PH model is formulated. For the other three networks, similar approach can be considered.

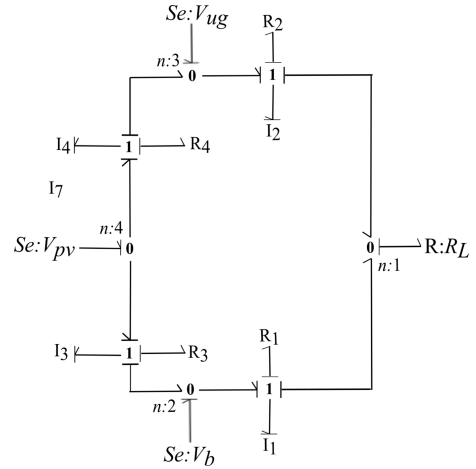


Fig. 12. Bond Graph of the DC micogrid's central transmission network.

Hence, referring to the network edges, we conclude in the following state-space representation :

$$\begin{cases} \begin{bmatrix} \dot{p}_{1c} \\ \dot{p}_{2c} \\ \dot{p}_{3c} \\ \dot{p}_{4c} \end{bmatrix} = [J_c - R_c]Q_c x_c + \begin{bmatrix} 0 & 0 & -1 & 1 \\ 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{pv} \\ -v_{ug} \\ -v_b \\ -v_{R_L} \end{bmatrix}, \\ \begin{bmatrix} i_{pv} \\ i_{ug} \\ i_b \\ i_{R_L} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & -1 & 0 & 1 \\ -1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix} Q_c x_c, \end{cases} \quad (11)$$

where $x_c = [p_{1c} \ p_{2c} \ p_{3c} \ p_{4c}]^T \in R^{1 \times 4}$ is the state vector, $u_c = [v_{pv} \ -v_{ug} \ -v_b \ -v_{R_L}]^T \in R^{1 \times 4}$ is the input vector and $y_c = [i_{pv} \ i_{ug} \ i_b \ i_{R_L}]^T \in R^{1 \times 4}$ is the output vector of the system. The skew-symmetric matrix J_c is equal to 0 and the dissipation matrix $R_c \in R^{4 \times 4}$ is equal to:

$$R_c = \text{diag}(R_{1c}, R_{2c}, R_{3c}, R_{4c}). \quad (12)$$

In order to obtain the explicit internal formulation of the system, we pass through the kernel representation (Golo et al., 2000) of the Dirac structure in Fig.12 and conclude in the following hybrid input-output representation:

$$\begin{bmatrix} e_I \\ f_{R,S} \end{bmatrix} = \begin{bmatrix} J_{(4,4)} & J_{(4,8)} \\ -J_{(4,8)}^T & J_{(8,8)} \end{bmatrix} \begin{bmatrix} f_I \\ e_{R,S} \end{bmatrix}, \quad (13)$$

where $J_{(4,4)} \in R^{4 \times 4}$ and $J_{(8,8)} \in R^{8 \times 8}$ are equal to 0, e_I and $f_{R,S}$ are the efforts of the four inductors and the flows of the resistors, the sources and the loads. On the other side, we have the flows f_I of the four inductors and the efforts $e_{R,S}$ of the resistors, the sources and the loads correspondingly. The matrix $J_{(4,8)} \in R^{4 \times 8}$ is equal to:

$$J_{(4,8)} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & -1 & 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & -1 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & -1 & 1 & 0 & 0 \end{bmatrix}. \quad (14)$$

Afterwards, in order to establish the control part, it is necessary to derive the constraints of the system. Primarily, we will concentrate on the minimization of the power losses, result of the Joule heating effect. The power P that is dissipated and converted to thermal energy is equal to:

$$P = (v_{inl} - v_{outl})i_l = i_l^2 R_l, \quad (15)$$

where i_l is the current of each transmission line resistor R_l . In Fig. 13 we illustrate the power losses of two different directions. The input voltage of the transmission lines that has been used for the simulation is equal to the common DC bus voltage (400V).

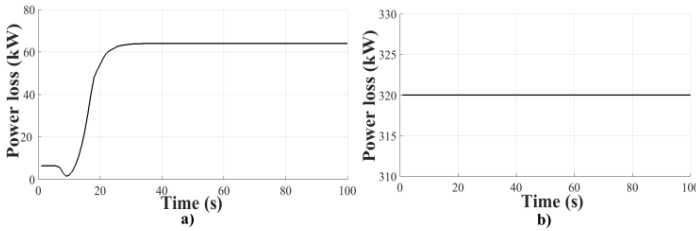


Fig. 13. Comparison of the power dissipation between two directions: a) from the PV to the load R_L through the ES and b) from the PV to the load R_L through the UG.

4. CONCLUSIONS

In this paper, we presented a model of a meshed DC microgrid and its Bond Graph. This representation helped in providing the port-Hamiltonian modelling of each microgrid component. We analysed each part separately based on the Bond Graph theory and its port-Hamiltonian representations. The global model takes into account the non-linear dynamics coming from the switching behaviour of the DC/DC converters. We developed explicitly the mathematical models of each subsystem separately and we described the power exchange among the components.

This primary mathematical analysis is very important and necessary for the design of a controller to deal with the load balancing problem within the microgrid. Finally, we gave some insights on the load balancing problem of the system by using the notion of a cyclic network. Future work will concentrate on integrating the developed model in an optimization-based control approach which takes explicitly into account the system's dynamics, cost, constraints, reference profiles and deals with various types of faults.

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