



HAL
open science

Sustainable-Driven Methodology for Two-Stage Energy Management Circuits for IoT Nodes

Niloufar Dizangian, Slavisa Jovanovic, Philippe Poure

► **To cite this version:**

Niloufar Dizangian, Slavisa Jovanovic, Philippe Poure. Sustainable-Driven Methodology for Two-Stage Energy Management Circuits for IoT Nodes. 31st IEEE International Conference on Electronics, Circuits and Systems (ICECS 2024), Nov 2024, Nancy, France. 10.1109/ICECS61496.2024.10848894 . hal-04955247

HAL Id: hal-04955247

<https://hal.science/hal-04955247v1>

Submitted on 18 Feb 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Sustainable-driven methodology for two-stage energy management circuits for IoT nodes

Niloufar DIZANGIAN, Slavisa JOVANOVIĆ and Philippe POURE
Université de Lorraine, CNRS, IJL, F-54000 Nancy, France
firstName.lastName@univ-lorraine.fr

Abstract—In this paper, a sustainability-driven methodology is proposed for the energy management of IoT nodes. The proposed methodology consists in the use of batteryless solutions and by introducing fault-tolerant capabilities in each stage of the energy management circuits to increase their overall reliability. By using equivalent synchronous switches with suitable control, a two-stage DC/DC converter can be made fault-tolerant. The proposed methodology has been applied to two different two stage cascaded converters (Buck/Buck-Boost and Boost/Buck) and validated by simulation in realistic IoT node conditions by using SystemC-AMS framework. The simulations have shown the effectiveness of the proposed methodology in realistic faulty conditions, and confirm that the continuity of service is guaranteed in Open Circuit Switch Fault (OCF) case, whatever the converter is concerned by the switch failure.

Index Terms—Sustainability, switch failure, fault tolerant operation, Cascaded converter, DC-DC converter, open-circuit failure, two-stage converter, Buck, Boost, Buck-Boost, Synchronous redundant switch.

I. INTRODUCTION

In the era where the world is witnessing from day to day perceptible climate changes due to the greenhouse gas (GHG) emissions from human activities, a myriad of different solutions are presented as potential candidates to address climate change related problems [1]. One of the solutions identified recently at World Economic Forum as a key technology in fighting climate changes is Internet-of-things (IoT) infrastructure and accompanying technologies [2]. IoT technologies are mainly seen as a worthwhile investment whose benefits will allow to control and reduce at the long run the GHG emissions and contribute in a general manner to net-zero solutions [3]. However, this initial investment, although with potential long-run benefits, contributes also to the GHG emissions at different levels: manufacturing, design, use [4].

Recently, the numerous initiatives have proposed solutions towards building sustainable IoT nodes and systems [4]. Thus, the sustainability can be incorporated at different levels: at the design level by proposing for instance energy-efficient operation; at the implementation level by using energy and material efficient technologies; at the usage level by using batteryless and maintenance free solutions; and at the end-of-life level by recycling or for instance repurposing the system for other goals. Consequently, these sustainability-driven design approaches should be more than a simple guideline but adopted by all IoT makers, whatever level of designing.

Energy management is the crucial part of IoT nodes, especially the ones supplied by energy harvesting sources. Whatever the type of the source used to supply IoT nodes

(thermoelectricity - TEG, photovoltaic - PV, etc.), the available energy at a given time should be extracted and conditioned to be usable by the IoT nodes for their processing tasks. Thus, the energy management circuits of IoT nodes usually comprise two stages, as depicted in Fig. 1. The first stage is the energy extraction stage ensuring the Maximum-Power-Point Tracking (MPPT) from a given source, whereas the second one is the voltage regulation needed to be stable for IoT processing nodes (i.e. CPU). These two stages are usually connected with a non-environmentally storage element such as a battery and driven with a suitable but often rigid control. On the other hand, in order to have a *left-behind* environmental friendly IoT node and to reduce to zero maintenance costs, all of its parts should be as much as possible resilient and based on sustainable technologies.

In this work, we propose a methodology to build sustainable-by-use and by design energy management circuits for IoT nodes. The sustainability by use is obtained by proposing fault-tolerant capabilities in the conversion circuits and by using batteryless solutions, whereas the sustainability by use is achieved by proposing energy management techniques allowing to adapt the circuits to different energy management scenarios. The proposed methodology is applied on two different conversion circuits topologies. The proposed conversion circuits are simulated and validated in realistic IoT node conditions by using SystemC-AMS framework.

This paper is organized as follows. Section II presents the basic idea of the proposed methodology which is based on an asynchronous or synchronous control in healthy conditions and synchronous post-fault operation, and was applied to two different two-stages converter circuits. Section III gives the results of simulation of one of the used converter topology in different realistic scenarios. Some conclusions and perspectives are given in Section IV.

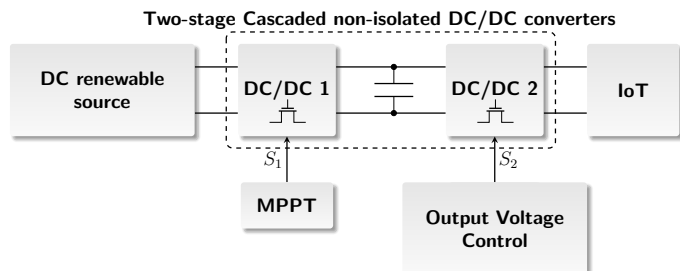


Fig. 1: Energy management part of an IoT node

II. PROPOSED FAULT TOLERANT METHODOLOGY

A. Principle of the fault tolerant approach

The proposed methodology is based on the equivalence between two switches sharing the same node (i.e. drain-source, source-source, ...) on which the suited synchronous control in post fault operation mode is applied. Consequently, this switch equivalence allows to introduce a reduced number of redundant switches in the initial topology and makes it fault tolerant. Moreover, the proposed methodology enhances the overall reliability of the converter topology and make it more sustainable.

In this work, the fault tolerant operation of cascaded DC-DC converters is considered only under OCF. For the type of converter to use in the cascaded topology, any single-switch non isolated DC-DC converter, such as a Buck, a Boost or a Buck-Boost can be used. In the classical approaches, fault tolerant circuit design mostly lays on switch redundancy; each of the two cascaded converters is usually considered separately, or sometimes both converters can be considered together if it is possible to share a common redundant switch associated with linking components. The new circuit design approach we propose is based on the synchronous equivalent switches presented in Section II-C. If the two switches S_1 and S_2 are synchronously controlled, these switches sharing a common node are equivalent to a three ports synchronous switch, based on a single switch and two diodes.

In the proposed approach, the design of the fault tolerant two-stage DC-DC circuit first consists on moving towards each other the two switches while maintaining the same electrical behavior of the converter. Thus, the two switches share a common node (for instance, drain (D) or source (S)) in the resulting equivalent electrical circuit and correspond to one of the two equivalent synchronous switches in Fig. 3. To obtain the final fault tolerant conversion circuit, the suited three-port equivalent synchronous switch previously obtained as the redundant counterpart for the two main switches is added to the initial circuit, in offline scheme. In Fig. 4 and Fig. 5, two examples of the use of the proposed methodology are provided for classical two-stage DC-DC conversion topologies: a Buck/Buck-Boost and a Boost/Buck.

B. Asynchronous / Synchronous control in healthy condition

Under healthy operating conditions, switches S_1 and S_2 are driven either asynchronously with signals δ_1 and δ_2 , or synchronously by the same control signals δ , as depicted in Fig. 2. If driven asynchronously, each signal (δ_1 and δ_2) controls the corresponding stage by modifying the duty ratio and/or frequency of these two control signals. On the other hand, if driven synchronously, the same signal δ should be used to drive both stages: to track the maximum power point (MPP) with the first stage using a maximum power point tracking (MPPT) algorithm, and to regulate the output voltage across the IoT node with the second stage. In order to control these two conversion stages independently in asynchronous control with a single control signal, they must operate in

different conduction modes. Therefore, the Discontinuous Conduction Mode (DCM) has been chosen for the first stage converter, whereas Continuous Conduction Mode (CCM) is the conduction mode of the second stage converter. This choice is justified by the fact that the output load must be permanently supplied with power, and thus, the inductor L_2 should operate in CCM while L_1 in DCM. This synchronous control approach simplifies the control circuit but reduces the available control variables compared to asynchronous control (from 4 (the frequencies f_1 and f_2 , and the duty ratios D_1 and D_2) to 2). In synchronous operation, only two variables dictate the behavior of the entire two-stage system as depicted in Fig. 2: the duty ratio (D) and the frequency (f) of the control signal (δ) applied to both S_1 and S_2 .

C. Equivalent three port synchronous switches

Fig. 3(a) depicts two switches, S_1 and S_2 , with a shared drain-source node, whereas Fig. 3(b) depicts these two switches with a shared source-source node. When a synchronous control signal is applied to both switches in one of these cases, their functionality becomes equivalent to a single synchronous switch S with associated diodes D_3 and D_4 [5] (the right side of the Fig. 3 (a) and (b)). However, this equivalence in electrical behavior is contingent upon the application of a synchronous control signal to both S_1 and S_2 .

D. Proposed fault tolerant methodology for 2 cases

The proposed fault tolerant methodology has been applied to two different topologies: a Buck/Buck-Boost converter and a Boost/Buck converter. Figures 4 and 5 illustrate the results of the addition of the fault-tolerant capabilities to these two topologies, respectively. For the Buck/Buck-Boost converter depicted in Fig. 4, the equivalent synchronous switch with $D - S$ (D - drain, S - source) common node has been used to provide fault-tolerant capabilities, whereas for the Boost/Buck converter depicted in Fig. 5, the equivalent synchronous switch with $S - S$ common node has been employed. The resultant fault-tolerant two-stage topologies separated with a supercapacitor are presented in Figs. 4(b) and 5(b). In both resultant

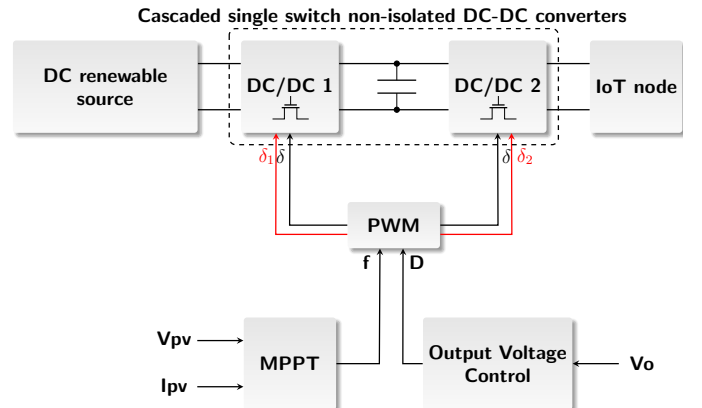


Fig. 2: Classical energy harvesting system with asynchronous (in red)/synchronous control for renewable DC sources.

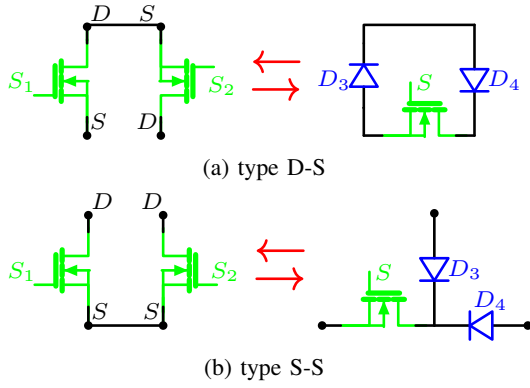


Fig. 3: Illustration of synchronous switch equivalent circuits.

circuits, the three switches are never used simultaneously: only switches S_1 and S_2 can be driven at the same time (asynchronously or synchronously), or only the synchronous switch S . The switching from driving S_1/S_2 switches to only synchronous switch S is carried out upon the fault detection in one of the two switches (S_1 or S_2).

E. Fault tolerant operation

Under normal operating conditions (healthy mode), a single pulse-width modulation (PWM) block synchronously controls both DC-DC converter stages if the converter operates synchronously (see Fig. 6), or two different control signals are generated for both switches S_1 and S_2 , if driven asynchronously. If driven synchronously as depicted in Fig. 6, the PWM block generates a switching pattern δ based on control variables: duty cycle D and frequency f . To ensure continuous power delivery to the connected load, the duty cycle parameter D controls the second converter (and thus regulates the output voltage), maintaining inductor L_2 in the second stage in the CCM. Conversely, the first converter is controlled by the frequency parameter f (and ensuring MPPT), forcing inductor L_1 in the first stage to operate in DCM. In the event of an OCF detected on either switch S_1 and/or S_2 , the

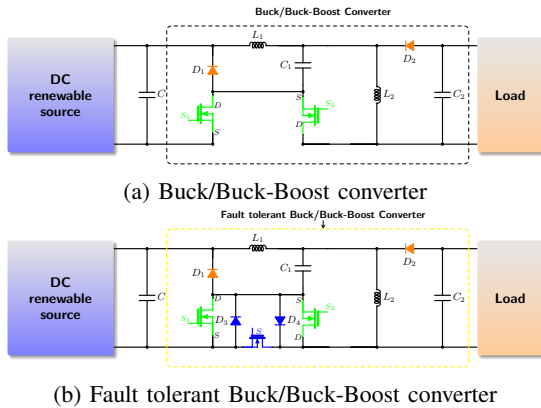


Fig. 4: Illustration of Buck/Buck-Boost two-stage converter and the proposed fault tolerant circuit.

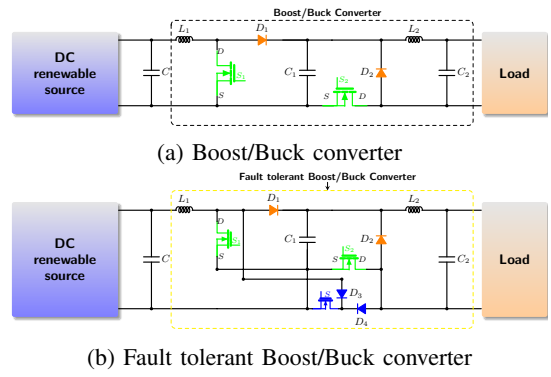


Fig. 5: Illustration of Boost/Buck two-stage converter and the proposed fault tolerant circuit.

control signals δ_1 and δ_2 to these two switches are disabled, and the switching pattern δ is applied to the single redundant synchronous switch S . This strategy ensures the system to maintain in the same operating point before and after the fault due to the equivalent circuit behavior under synchronous control. Consequently, the reconfigured circuit retains its full functionality after a switch failure without any performance degradation.

III. Simulation results for Buck/Buck-Boost converter

This paper investigates the fault tolerance capabilities of a two-stage Buck/Buck-Boost converter under OCF conditions. The two-stage converter is controlled asynchronously in healthy conditions and synchronously when a fault occurs on one of the two switches. The proposed converter has been modeled with the SystemC-AMS by using the parameters presented in Table I. As a DC renewable source, a thermoelectric generator (TEG) with an internal resistance of 13.4Ω has been used. The open circuit voltage V_{OC} of the TEG evolved continuously in the range of 2 to 4V. The MPPT of the TEG is ensured when the voltage at the input of the first stage has the half of the value of V_{OC} . As the MPPT algorithm, a hysteresis-based algorithm has been used

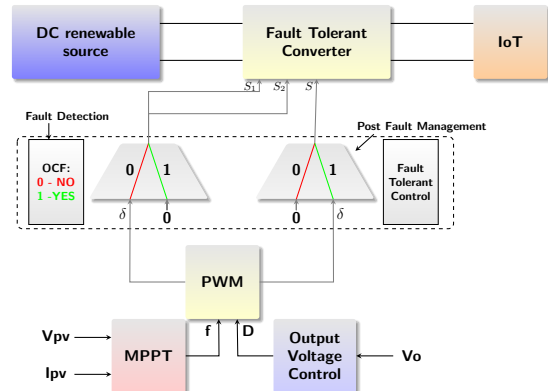


Fig. 6: Principle of the reconfigurable synchronous control for healthy condition and fault tolerant operation at full rate.

ensuring that the input voltage of the first stage is around $\frac{V_{OC}}{2}$. For the IoT node, the power consumption profile from the Messy framework [6] has been extracted and loaded into the proposed framework. The use case of a RISC-V node reading and writing the sensors and corresponding to a load current around 250 mA has been used. Moreover, an additional power consumption of the same amount has been estimated for the power management and driving of the switches of this fault-tolerant two-stage converter. The simulation results are presented in Figs. 7, Fig. 8 and Fig. 9. Fig. 7 shows the currents shapes of the inductors L_1 and L_2 . It can be seen that the first stage is in DCM whereas the second stage is in CCM mode, the operating modes ensuring the smooth switching to the synchronous mode of operation as explained previously.

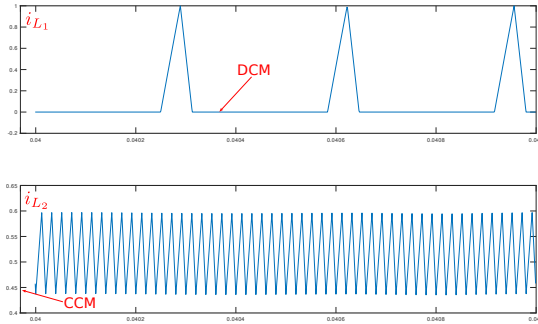


Fig. 7: Currents waveforms for inductors L_1 in DCM mode and L_2 in CCM mode in healthy mode (asynchronous control) for Buck/Buck-Boost converter.

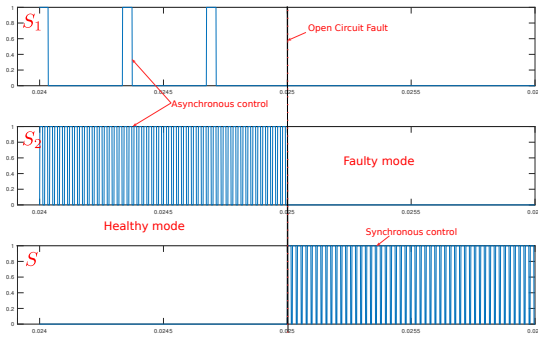


Fig. 8: Switching Pattern for S_1 , S_2 and S during the transition from healthy to faulty mode for Buck/Buck-Boost converter.

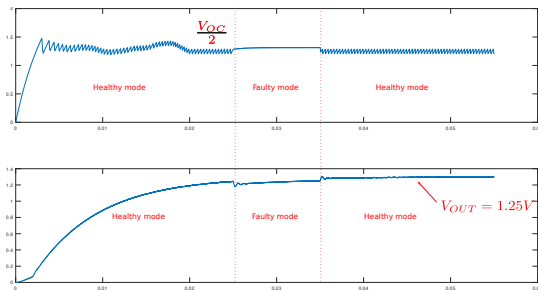


Fig. 9: First stage input voltage waveform and the output voltage regulation for Buck/Buck-Boost converter.

Fig. 8 shows the switching pattern from the healthy to faulty mode. It can be seen that the switches S_1 and S_2 are not driven any more and that only the switch S is driven by the control logic. Fig. 9 shows the start up of the system and the transient responses for both the input voltage of the first stage and the regulated output voltage. It can be seen that the input voltage of the first stage follows the dynamics of the TEG voltage V_{OC} and is continuously at $\frac{V_{OC}}{2}$ and thus ensures the MPPT. Moreover, the output voltage regulation at 1.25V is also shown on the bottom of this figure. An OCF is simulated during 10ms (between 25 and 35 ms). It can be seen that the continuity of the operation in terms of MPPT and output voltage regulation has been ensured during this period.

TABLE I: Parameters of the fault-tolerant converters.

parameters	Value
V_{in}	10V
V_B	5V
R_L	2.5Ω
L_1	$50\mu\text{H}$
L_2	$100\mu\text{H}$
C	$330\mu\text{F}$
C_1	$100\mu\text{F}$
C_2	$100\mu\text{F}$
f_{2s}	50 kHz
D	56%

IV. CONCLUSION

In this paper, a sustainability-driven methodology has been proposed for the energy management of an IoT node. The proposed methodology consists in the use of batteryless solutions and by introducing the fault-tolerant capabilities in the energy management circuits to increase their overall reliability. This methodology is based on the use of equivalent synchronous switches with suitable control allowing to apply the fault-tolerant capabilities to the two switches in the cascaded DC/DC converters and has been applied to two different two stage cascaded converters and validated by simulation in realistic IoT node conditions by using SystemC-AMS framework. The simulations have shown the effectiveness of the proposed methodology in building sustainable energy management circuits for IoT node. As perspectives, the validation of the proposed methodology in experimental conditions with different scenarios will be carried out in the near future.

REFERENCES

- [1] H. Nguyen-An *et al.*, "IoT Traffic: Modeling and Measurement Experiments," *IoT*, vol. 2, no. 1, pp. 140–162, Feb. 2021.
- [2] W. E. Forum, "Future of the Connected World: A Roadmap for Mobilizing Global Action VISION, PROGRESS AND MEASURES OF SUCCESS," Tech. Rep., 2021.
- [3] Y. K. Dwivedi *et al.*, "Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action," *International Journal of Information Management*, vol. 63, p. 102456, Apr. 2022.
- [4] M. Katz *et al.*, "Towards truly sustainable IoT systems: The SUPERIOR project," *Journal of Physics: Photonics*, vol. 6, no. 1, p. 011001, Jan. 2024.
- [5] T.-F. Wu and T.-H. Yu, "Unified approach to developing single-stage power converters," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 34, no. 1, pp. 211–223, 1998.
- [6] M. A. Hamdi *et al.*, "Integrating systemc-ams power modeling with a risc-v iss for virtual prototyping of battery-operated embedded devices," *arXiv preprint arXiv:2404.01861*, 2024.