Phase-shedding in Boundary Conduction Mode Converter with Optimal Transition Load-level

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Abstract

Phase-shedding, one famous technology for multi-phase converters, is implemented in a bi-directional multi-phase converter for ESS. It reduces active operating modules at light load to compensate efficiency. Shedding point, the load level where the converter changes the number of active modules, is important factor that affects the effect of phase-shedding. Loss analysis is done for determining shedding point. Phase-shedding hysteresis is applied so that excessive phase transition is avoided. This paper proposes shedding point correction where the shedding point is adaptively corrected by calculating a new shedding point.

1. Introduction

Distributed power systems have emerged with development of renewable energy resources. Many of renewable energies, such as photovoltaics and wind-turbine, are affected by their weather conditions and often fail to generate expected electricity. For the reason, energy storage systems (ESS) are essential for the distributed power system with better efficiency and power quality.

Converter used in ESS is usually a high power DC-DC converter requiring few or more kilowatts. For the high power converters, interleaved multi-phase operation is an adequate choice [1-2]. By dividing power path into, for example, two phases, conduction loss can be reduced by factor of nearly two. Phases are interleaved to eliminate an amount of current ripple by shifting phases of each current [3].

To maintain high efficiency at wide load range, phase-shedding is widely implemented [4-6]. At the lighter load, switching losses become large which is resulted in efficiency deficit. However, multi-phase converters are equipped with two times of switching elements so that the switching loss is doubled. The purpose of phase-shedding is to enhance converter efficiency at light load by running a single module.

This paper focuses on this phase-shedding scheme, especially about when and how to 'shed the phases'. First step is to determine the appropriate load level of phase-shedding. Loss analysis is conducted to choose the initial shedding point. Hysteresis is exploited in phase-shedding to avoid frequent transition of modules which will invoke current deviation. The paper proposes 'shedding point correction' where the shedding point is corrected in real-time to maximize the effect of phase-shedding. During converter operation, the actual shedding point is estimated to vary according to operating environments of converter. With proposed algorithm, new shedding point is calculated.

Bi-directional frequency adaptive boundary-conduction-mode (BCM) dual-phase 200-W prototype converter is implemented [9]. Experiment data is following to check the transient of phase-shedding and efficiency improvement by phase-shedding.

2. Threshold load level for phase-shedding

2.1 Loss analysis at design stage

Loss analysis is prerequisite before deciding to apply phase-shedding [4]. Main loss components are listed as: conduction losses of FETs, diodes, and inductors; switching losses of FETs and diodes; core loss and capacitor ESR loss. [7-8] Varying load from 0A to 10A, loss components are depicted as Fig.1 on single-module based on the specification in Table.1. The figure shows: switching losses (turn-off loss, reverse recovery loss) are dominant at light load; conduction loss and core loss are dominant at heavy load.

Table.1. Converter specifications

Power Stage	Vin	38 V
	Vout	15-25 V
	Inductor	45 uH, 45 uH
	Filter capacitance	66 uF
MOSFET	Rds	13 mOhm
	Coss	610 nF
	Qrr	200 nC

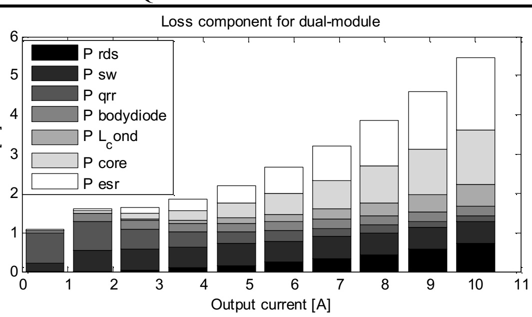

Fig.1. Loss components for dual-module

Experiments have been done for obtaining efficiencies. After revision of loss model, loss analysis data coincides with experiment results as depicted in Fig.2. The intersection of two curves, $I_{th}=2.3A$, is chosen to be the shedding point.

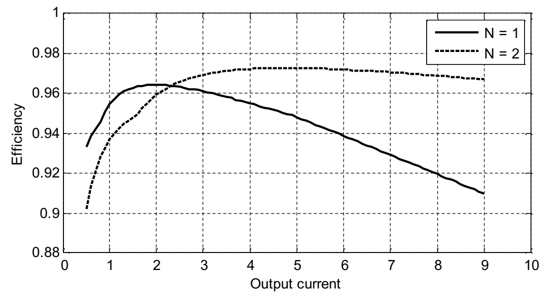

Fig.2. Efficiency curves with shedding point

2.2 Hysteresis on phase-shedding

There are few reasons that hysteresis phase-shedding is exploited: 1. Frequent phase-shedding causes unnecessary current deviation; 2. A Hall-effect based current sensor, ACS716 manufactured by Allegro®, has limited resolution of $Res=1061A$.

Hysteresis scheme is as shown in fig.3, and the window length is designed as $\delta=0.2A$. Size of hysteresis window should be analyzed more rigorously because larger window degenerates efficiency improvement of phase-shedding while small window brings redundant phase transitions.

2.3 Shedding point correction

Efficiency curves of actual converter fluctuate as components of the converter deteriorate during its life-time, or as characteristics

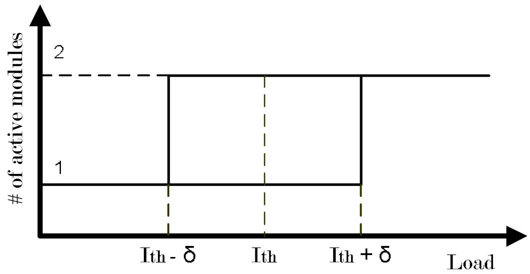

Fig.3. Hysteresis on phase-shedding

of them get worse according to thermal conditions. When actual efficiency curves vary from the pre-estimated ones, the actual optimum shedding point also varies.

This paper proposes an algorithm that corrects the shedding point adaptively, making the maximum use of phase-shedding. For bi-directional operation, this converter has sensors at both terminals, fortunately. Voltage and current information is multiplied in DSP to get efficiency information in real-time. Once a variation of efficiency is detected, digital control unit corrects the shedding point in the way described below.

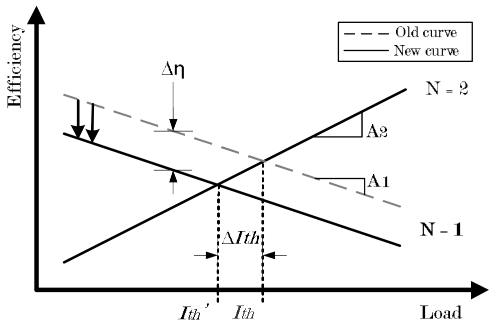

Fig.4. Shedding point correction

Fig.3 gives illuminating description about shedding point correction. For it is impossible to get efficiency curves and their slopes at every condition, we assume slopes of efficiency curves are linear near the shedding point. The slopes are expressed as:

$$A_1 = \left.\frac{\partial \eta_1}{\partial i_o}\right|_{i_o=I_{th}} \qquad A_2 = \left.\frac{\partial \eta_2}{\partial i_o}\right|_{i_o=I_{th}}$$

where A_j (j=1, 2) is slope of the curve at shedding point $i_o=I_{th}$. Once a certain amount of efficiency variation, $\Delta\eta$, at single-module operation is detected, a new shedding point, I'_{th}, is calculated as:

$$I'_{th} = I_{th} + \Delta I_{th}\,, \quad \text{where } \Delta I_{th} \approx \frac{\Delta\eta}{A_2 - A_1}$$

It is easily inferred from the equations and the figure that decrease of efficiency at single-module leads to decrease of shedding point, and vice versa. However, as long as this shedding point correction assumes linearity of efficiency curves, error will be accumulated as repeated correction. The converter doesn't know how wrong the point is unless efficiency curves are swept for the whole load range. It can be assumed that actual optimum shedding point will not go away from the original value because single and dual-module cases share the same tendency about degeneration of efficiency. So, within a certain variation range of shedding point, I_{th_min} to I_{th_max} , shedding point is determined.

3. Experiment

Fig.5 depicts the transient of phase-shedding moment. After the load gets lower than the shedding point, the slave module stops operating. In Fig.6, the curves with and without phase-shedding are plotted together for comparison.

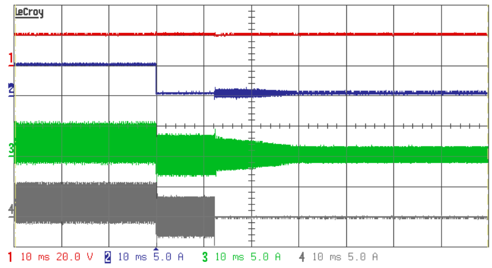

Fig.5 Phase-shedding transient

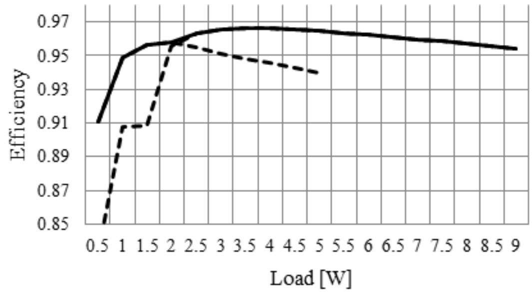

Fig.7. Improved efficiency by phase-shedding

4. Conclusion

Phase-shedding is applied in bi-directional multi-phase converter. Applicability of it has been proven before the implementation, and the optimum shedding point is derived after loss model revision. According to variation of operating conditions and circuit elements, shedding point is adaptively corrected. It is expected to maximize the effect of phase-shedding, but error accumulation is probable which was prohibited by limiting variation of the point. Hysteresis on phase-shedding is designed to inhibit frequent change of the number of active modules. More rigorous analysis should be done to figure out the tradeoff in design hysteresis. Experiment proved efficiency improvement by phase-shedding.

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