ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2010. No. 3(99)
ELEKTRONIKA IR ELEKTROTECHNIKA

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Evaluation of Efficiency of Active Clamp Dual Flyback Inverter for Photovoltaic Systems using Simulation Method

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Introduction

Dual flyback inverter (DFBI) is one of the preferred topologies for isolated low cost low power photovoltaic (PV) applications. It converts PV cells DC voltage to output AC voltage using single power stage. It is important to understand loss distribution of DFBI be able to reach efficiency limits of this topology. This paper evaluates the efficiency of DFBI based on computer simulation results worked-out by Simetrix circuit simulator.

Operation of dual flyback inverter

Theory of operation of DFBI is described in [1] and others. There is performed the simulation of this topology with standard *RC* clamp, and shortly described other clamping circuits. It makes sense to carefully analyze the efficiency of DFBI with lossless clamping circuits, as the efficiency of PV inverter is one of most important parameters for each PV application. The schematic of DFBI with lossless active clamp is in Fig. 1.

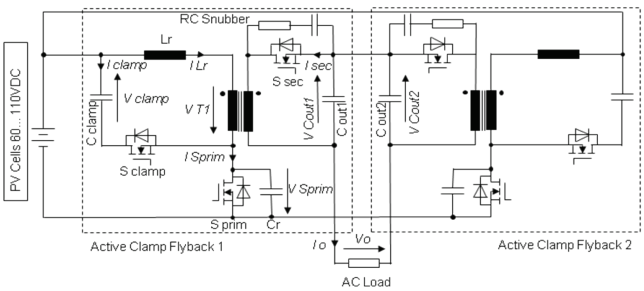

Fig. 1. Circuit diagram of dual flyback inverter with active clamp circuit

The DFBI consists from two bidirectional flyback converters. Each of them operates with one polarity of output voltage $v_{Cout,,}$ and two polarities of output current i_{sec}. This two-quadrant topology with an appropriate control allows to create harmonic voltages with DC bias on both output capacitors C_{out1}, C_{out2} for all types of AC loads (R, L, C and not harmonic also).

If the DC bias voltages of C_{out1}, C_{out2} are equal, then output voltage is harmonical without DC bias ([1], page 10/38). There is possibility to significantly enhance the performance of flyback converter, by adding active clamp to this topology (L_r, C_{clamp}, S_{clamp}). The clamping circuit recycles the energy stored in inductance L_r (composition of leakage inductance of transformer and external discrete inductor), and in addition allows ZVS switching of S_{prim1}, S_{prim2}. It is important to notice, that it can reduce the rectifier losses (S_{sec}). The operation of active clamp is described in [2].

Modelling and simulation of DFBI

There are different simulation tools on market which are suitable for simulation of power electronic circuits. Simulation tool which should be used for simulation of power converter efficiency has to include sophisticated models of power switching devices together with advanced models of magnetic circuits (including magnetic core selection for evaluation of losses in magnetic material, coupling factor selection and saturation current overview after definition of turn number of windings). The simulation tool SIMETRIX meets criteria above.

Following losses has been included in simulation model of active clamp DFBI:

- Switching and conduction losses of semiconductors (diodes, MOSFETs);
- Copper losses of wound components (excluding skin effect);
- Magnetic core losses of wound components;
- ESR losses of capacitors;
- Standard power losses of resistors (snubber circuits).

Simulation model in present state does not include:

- Skin effect losses in wound components;
- PV capacitor losses (DFBI should have on the input large capacitor due to input power

fluctuation. The capacitor will ensure that PV cells will operate with constant output power in MPP point);

- Estimated losses of DFBI control circuits (this type of losses significantly reduces the efficiency of power converter at light load).

The simulation has been performed with following parameters:

- Input voltage range of DFBI Vimin = 60VDC, Vimax = 110VDC;
- Nominal output power of DFBI Ponom = 600W;
- Nominal output voltage Vo = 230VAC;
- Switching frequency of DFBIs fsw = 20kHz;
- DFBI running in off grid (island) operation with resistive load on the output;
- 40ms transient analysis with default simulation options.

Results achieved by Simetrix simulation

Two line frequency periods of output waveforms of DFBI are shown on Fig. 2. It is obvious, that voltages of output capacitors v_{Cout1}, v_{Cout2} are quasi-harmonic with DC bias voltage slightly higher than amplitude of harmonic voltages (slightly higher means cca 20V - what allows converter good forming of output voltage in regions where capacitors voltages are nearly zero). The output voltage v_o is quasi harmonic without DC bias. The output current i_o is proportional to output voltage, as the load has resistive character. Three PWM cycles of DFBI are on Fig. 3 and Fig. 4. All the curves are comparable with standard active clamp flyback theory. Interesting point is oscillation visible on primary transformer voltage v_{T1}. The oscillation occurs during the commutation from rectifier MOSFET (S_{sec}) to primary MOSFET (S_{prim}). The oscillation means additional losses in DFBI (snubber circuit losses, reverse recovery losses of slow body diode of MOSFET S_{sec}). It may happen that oscillation is so high, that it will reach avalanche region of MOSFET S_{sec}, what means additional switching losses also (it is expected that modern MOSFET are rated for repetitive avalanche operation). Fig.5 shows efficiencies of DFBI in different operating modes. As visible, the simulation has been performed with two values of L_r inductance, which directly influences the losses during the commutation from MOSFET S_{sec} to MOSFET S_{prim}. Figure shows, that maximum efficiency of converter has been reached at V_{imax} and L_r = 3uH. It has to be noticed, L_r = 3uH at V_{imax} means that pure ZVS switching of MOSFET S_{prim} is no more reached (due to insufficient energy stored in L_r). Nevertheless, L_r = 3uH will mean lower rectifier (S_{sec}) losses in comparison to L_r=10uH. Fig. 5 shows, that active clamp DFBI has good efficiency in wide range of loads. This is extremely important for PV inverters, as they are compared by Euro-efficiency parameter. The figure compares the efficiency of active clamp DFBI and standard RC clamp DFBI also. It is obvious that efficiency of RC clamp DFBI is significantly lower in comparison to efficiency of active clamp DFBI (nearly 10% lower at nominal load). In addition the RC clamp DFBI efficiency drops down much faster in comparison to active clamp DFBI (with decreasing of load). These facts justify the usage of active clamp circuit for DFBI PV inverter even if it means additional component cost.

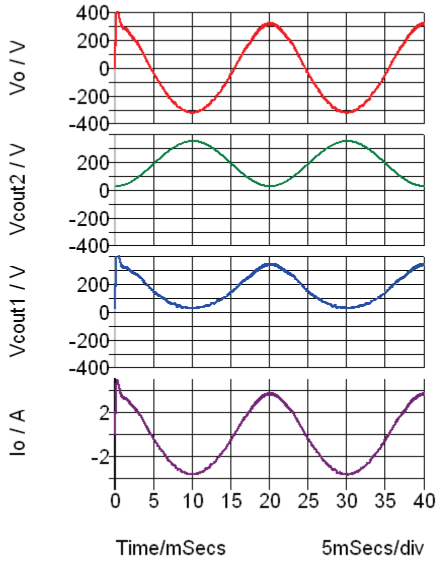

Fig. 2. Output waveforms of DFBI

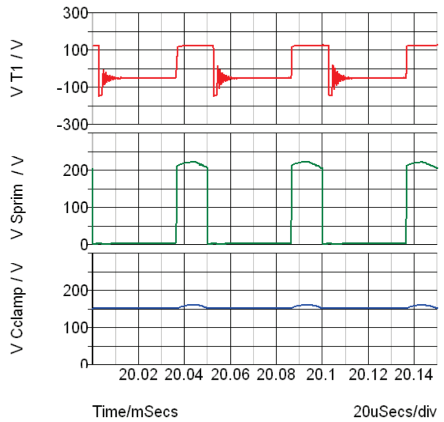

Fig. 3. Three PWM cycles of DFBI

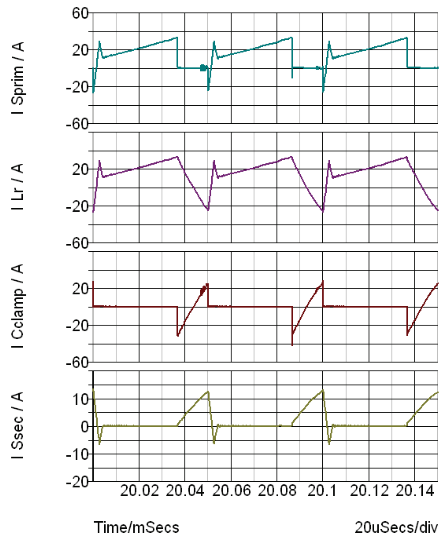

Fig. 4. Three PWM cycles of DFBI

The European annual efficiency (Euro-efficiency) is calculated according to Eq. (1). The index value means percent of nominal power.

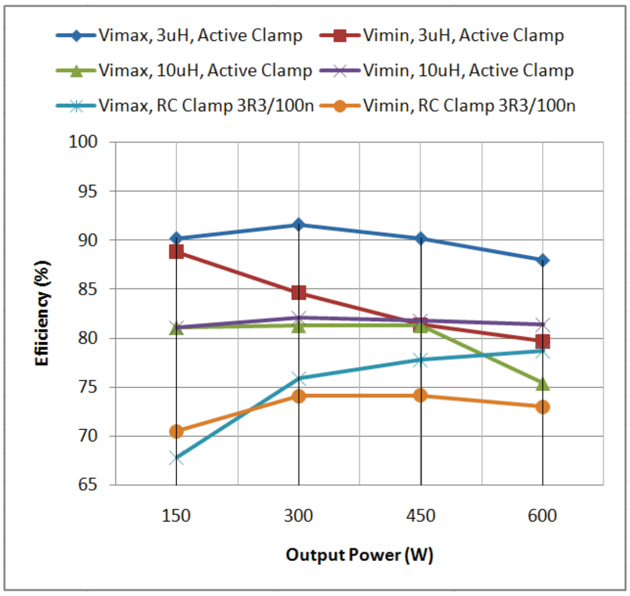

Fig. 5. Efficiency of DFBI in different operating conditions

Table. 1 Calculation of Euro-efficiency for active clamp DFBI and standard RC clamp DFBI

	Vimax, 3uH, Active Clamp	Vimax, RC Clamp 3R3/100n
η_5	70,8%	32,2%
η_{10}	82,5%	48,8%
η_{20}	88,5%	64,1%
η_{30}	90,3%	70,8%
η_{50}	91,6%	75,9%
η_{100}	88,0%	78,7%
η_{EU}	89,2%	71,5%

$$\eta_{EU} = 0{,}03 \cdot \eta_5 + 0{,}06 \cdot \eta_{10} + 0{,}13 \cdot \eta_{20} + \\ + 0{,}10 \cdot \eta_{30} + 0{,}48 \cdot \eta_{50} + 0{,}20 \cdot \eta_{100} \quad (1)$$

Table 1 confirms the statements which were mentioned above for Fig. 5. The calculated Euro-efficiency for active clamp DFBI is nearly 20% higher than Euro-efficiency of RC clamp DFBI. If the active clamp DFBI will be even more optimized it will be most probably possible to reach Euro-efficiency over 90%. This will mean that active clamp DFBI topology will be comparable with other isolated high efficiency PV topologies which are more expensive.

Fig. 6 shows the loss distribution in different operating modes of active clamp DFBI. It is clearly visible, that most important from loss point of view are primary semiconductors then wound components, and finally secondary semiconductors. The rest of losses are minor.

Table. 2 Loss distribution overview by components

Component	L_{oss}@V_{imin}, P_{onom}, Lr = 3uH [W]	Loss@Vimax, Ponom, Lr = 3uH [W]
L_r	0,88	0,295
C_{clamp}	0,82	0,42
T1	15	9,02
S_{clamp}	4,7	7,67
S_{prim}	49,14	12,6
C_r	0,66	0,2
S_{sec}	5,14	7,13
RC snubber	1,5	0,99
C_{out}	1,6	1,05

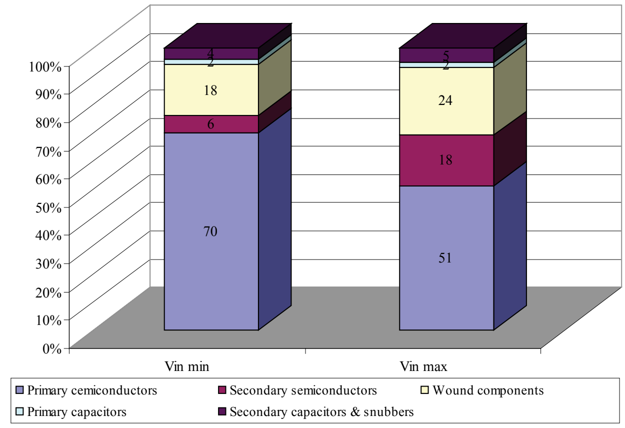

Fig. 6. Loss distribution in different operating modes

Considering of SiC diodes

Commutation from slow MOSFET body diode S_{sec} to primary MOSFET S_{prim} is important from switching losses point of view (as mentioned in chapter 3). It is expected, that adding of fast diode in parallel with MOSFET S_{sec} body diode can reduce the reverse recovery losses in S_{sec} and RC snubber on secondary side. Fig.7 compares reverse recovery characteristics of different diodes. The best choice for DFBI seems to be usage of silicon carbide diode (for example SDT06S60 type). This diode has lowest reverse recovery charge Q_{rr}. The performance of active clamp DFBI with SiC diode on output has to be verified by appropriate simulation.

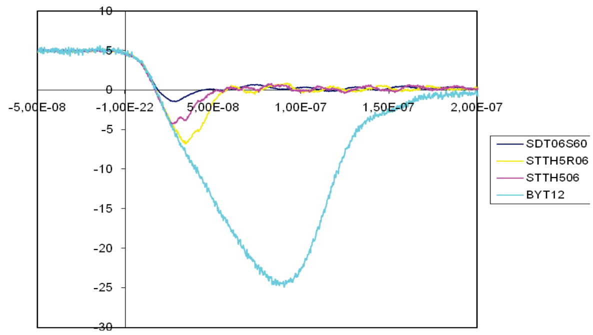

Fig. 7. Reverse recovery characteristics of different diodes

Conclusion

The efficiency of active clamp flyback has been evaluated and simulated. Three main types of losses were identified. It was found out, that there is no need to directly reach the ZVS switching of primary MOSFET Sprim (by choosing appropriate L_r), but it is necessary to optimize commutation from output MOSFET S_{sec} body diode to primary MOSFET S_{prim}. The highest efficiency has been reached without pure ZVS switching of primary MOSFET S_{prim}. It should be noticed, that most important parameters for PV inverters are efficiency and cost (the size/power density of inverter is not critical). The efficiency of active clamp DFBI is good in wide range of loads, which means that this topology is suitable for PV applications. The active clamp circuit significantly improves the efficiency of DFBI in comparison to standard RC clamp. It was found out that Euro-efficiency of active clamp DFBI is nearly 20% higher than standard RC clamp DFBI. This fact justifies additional cost which is required for implementing of active clamp circuit. The input PV capacitor has to be added to future simulations together with consumption estimation of control circuitry. In this case the simulation will become more accurate. The parallel SiC diode on secondary MOSFET has to be simulated also. Reached simulation results are sufficiently promising for building of experimental prototype in 2nd step.

Acknowledgements

The authors wish to thank for the support to the R&D operational program Centrum of excellence of power electronics systems and materials for their components, No.OPVaV-2008/2.1/01-SORO, ITMS26220120003 funded by European Community, for financial support to VEGA Agency for the project No. 1/0470/09 and project APVV VMSP-P-0085-09.

References

1. **Kjaer S. B., Blaabjerg F., Pedersen J. K.** Simulation of Inverters for PHOTOENERGY project. – Aalborg University, Alborg. – 2002. – P. 4–25.
2. **Dalal D.** Design Considerations of Active Clamp and Reset Technique. – Application note No. SLUP 112. – Texas Instruments. – 2001. – P. 1–5.
3. **Ogura K., Chandhaket S., Hirota Y., Hiraki E., Nakaoka M.** Small Scale Utility-Connected Solar Photovoltaic Power Conditioner using Soft-Switching High-Frequency Sinewave Modulated Inverter Link for Residential Applications. – Yamaguchi University, Yamaguchi. – Dec. 2002. – Vol. 52 No. 2. – P. 1–6.
4. **Chimento F., Dobrucký B.** DC–DC Converter for Renewable Energies Application with Maximum Power Point Tracking Operation. – Activity Report of Maria Curie ECON2. – Zilina. – May 2006. – P. 12–30.
5. **Chang L., Liu Z., Xue Y., Guo Z.** A Novel Buck-Boost Inverter for Photovoltaic Systems // Canadian Solar Buildings Conference. – Montreal. – August 2004. – P. 1–8.
6. **Dobrucky B., Spanik P., Sul R.** Improvement of Power Electronic Structure Characteristics Using SiC Technology – Overview // Communications – Scientific Letters ZU. – Zilina. – 2006. – Vol. 1. – P. 34–38.
7. **Sul R., Dobrucky B.** Structures Based on SiC Technology – New Possibilities, Properties and Application. (In Slovak) // Proceedings of Conference ERU 2006. – Brno. – Nov. 2006. – P. 1–11.
8. **Sul R.** Hybrid PV/FC- and Super C Renewable Energy Source Based on SiC Technology // Proceedings of Conference Liptovsky Mikulas. – Oct. 2007. – P. 30–36.
9. **Sul R., Frivaldsky M., Fibich P., Boggarpu N. K.** SiC in Power Semiconductor Devices (In Slovak) // Proceedings of IEEE Conference ZVULE. – Zvule. – Aug. 2008. – P. 268–271.
10. **Špánik P., Dobrucký B., Frívaldský M., Drgoňa P., Kurytnik I.** Measurement of switching losses in power transistor structure // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 2(82). – P. 75–78.

Received 2009 12 18

R. Šul, B. Dobrucký, P. Čerňan. Evaluation of Efficiency of Active Clamp Dual Flyback Inverter for Photovoltaic Systems using Simulation Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 3(99). – P. 23–26.

Dual flyback inverter (DFBI) is one of the preferred topologies for isolated low cost low power photovoltaic (PV) applications. It converts PV cells DC voltage to output AC voltage using single power stage. It is important to understand loss distribution of DFBI be able to reach efficiency limits of this topology. This paper evaluates the efficiency of DFBI based on computer simulation results worked-out by Simetrix circuit simulator. Ill. 7, bibl. 10 (in English; summaries in English, Russian and Lithuanian).

Р. Шул, Б. Добруцки, П. Чернан. Оценка эффективности активного клещевого DFBI инвертора фотоэлектрических систем используя метод имитации // Электроника и электротехника. – Каунас: Технология, 2010. – № 3(99). – С. 23–26.

Двойной инвертор DFBI является одной из наиболее популярных топологий для использования в изолированных фотоэлектрических элементах (PV) низкой стоимости. Он преобразует постоянное напряжение PV клеток на выходное напряжение переменного тока, используя одну ступень мощности. Понимая распределение энергетических потерь в DFBI, можно достичь пределы эффективности этой топологии. Эффективность DFBI оценена на основе результатов компьютерного моделирования схемы в программе «Simetrix». Ил. 7, библ. 10 (на английском языке; рефераты на английском, русском и литовском яз.).

R. Šul, B. Dobrucký, P. Čerňan. Fotogalvaninių sistemų DFBI inverterio efektyvumo nustatymas modeliavimo metodu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 3(99). – P. 23–26.

DFBI inverteris yra viena iš populiariausių topologijų, naudojamų izoliuotuose pigiuose mažos galios fotogalvaniniuose (PV) elementuose. Jis keičia PV celės nuolatinę įtampą į kintamą, naudodamas vieną galios pakopą. Norint pasiekti šios topologijos efektyvumo ribas, būtina suprasti DFBI energijos nuostolių pasiskirstymą. Šiuo tikslu naudojant kompiuterinį grandynų modeliavimą programa „Simetrix“, nustatomas DFBI efektyvumas. Il. 7, bibl. 10 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).