International Journal of New Computer Architectures and their Applications (IJNCAA) 8(4): 179-185
The Society of Digital Information and Wireless Communications, 2018 ISSN 2220-9085 (Online); ISSN 2412-3587 (Print)

Circuit Analyses and Considerations on Advanced Inverters Constructed by Minimum Circuit Components

- Pursuit for concise PCS of photovoltaic power generations -

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ABSTRACT

Photovoltaic power generations (PVG) have been used generally and applied widely. Various power conditioning systems-PCS used in PVG have been also working on by many researchers. In addition to usual utilization, such PVGs are often applied for the time of disaster. In such a way, the solar panels having limited power are almost installed in limited area such as on top of the roof of the building. Some medical institutions have fairly desire to keep such PVG since they must keep the lives of people. The generating power in such case is fair limited, so the system construction should balance the reduced power. In such reasons, it is important to construct toward simple one. In this paper, in order to give the reply, simple and concise PCS, especially novel inverter is considered. Considering fair reduced power and narrow space of installation, the system constructions should be much compact. The circuit strategy which gratifies their operating characteristic is presented and analytically discussed about circuit construction as advanced converter. The circuit operation is confirmed by using the circuit software constructed by PSpice.

KEYWORDS: Circuit software, PSpice, Power Conditioner, PCS, Solar cell, Minimum construction, Buck-boost inverter, Photovoltaic power generation

1 INTRODUCTION

In modern medical care, the development of the structural function in the operating room is remarkable [1,2]. The endoscopic surgery including surgical robot and the catheter intervention has been applied, so that such remarkable operating technics have been developed with robotic operating room and hybrid operating room. For almost electrical equipment using in such medical facilities, even instantaneous interruption should not be permitted. In general, by means of larger scale interruptible power supply installed by generator and batteries is provided. In such system, however, the system scale becomes large accompanied by high cost [3,4].

The PCS including inverter have been presented in various PVG, so far [3,4]. However, it is necessary to reduce the cost even more. It is said that the system is approaching to an ideal one with respect to efficiency and construction strategy, but that cost would prevent wide spread. In such discussions, there are many subjects to be solved to utilize the PV power in utility interactive power generation. Even more, various safeguard equipment required according to regulations make the cost increase. In fairly reduced power PCS as mentioned above used in limited facilities. In such case of reduced generating power, that is, in such PV power generation systems, there are so many subjects to be resolved [5-7].

The authors have been studied in a series of the small power PV system [7-9]. In this paper, some simple PCS systems, especially the components like inverters and chopper are integrated toward simple construction, which are presented and analyzed by using circuit software, PSpice. In the software, various techniques are originally and skillfully devised and presented. The whole result is analytically discussed.

2 PROPOSAL OF ADVANCED INVERTER

2.1 Circuit configuration

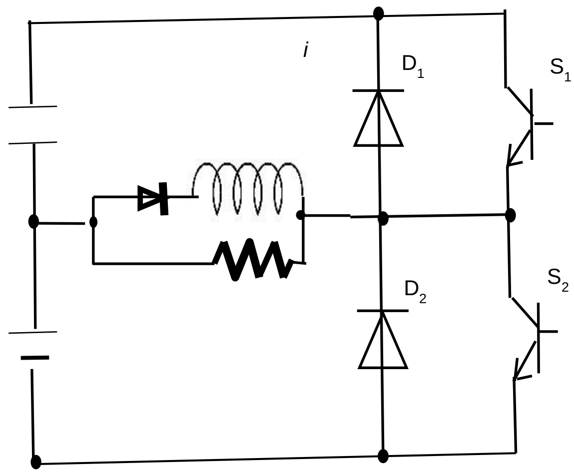


Figure 1. Proposed Advanced Inverter.

Fig.1 shows proposed circuit configuration having resistor load R. In comparison to the conventional high frequency inverter, where in half bridge circuit using boosted chopper, the obtained high frequency is rectified as dc-dc converter [8], the proposed configuration seems to be the same as the number of the circuit component

Fundamental construction is presented in the figure. Various derived circuit construction could be obtained from this circuit. With regard to the efficiency, however, the power conversion process of the proposed one is simple and the number of conversion stage is reduced, so the proposed circuit is prominent in comparison. Those validities are confirmed as follows;

When the switch S_2 is turned-on at the beginning, the power supply provides the load resistor R and inductor L in parallel connection. Secondly, when S_2 is turned-off and S_1 is turned-on, the stored energy in L is provided to R and at the same time the excess energy is delivered to the auxiliary capacitor. During last half period, as the supplied power from L is reduced gradually, a deficiency for supplied power from L is provided from auxiliary capacitor C. Looking at the whole period, it can be seen that the contribution for power transmission through inductor L is predominant. On the other hand, the power transmission through C is a role of auxiliary power transmission. The percentage of power transmission from L to R is about 30% at usual specification, while one from L to R through C is 20%. For your information, the one of the direct transmission E to R is 50%. It is interesting that the auxiliary capacitor C plays a role of like filter.

In Fig.2, the power transmission chart is represented, where the power line is plotted by heavy solid line. That transmitted power is fairly large, while thin line represents small power transmission. Looking at the whole period, it can be seen that the contribution for power transmission consists of direct transmission from E to R. In addition, the route through inductor L is also predominant. It is remarkable strategy that the power transmission is constructed by the direct transmission. Furthermore, as another route, one is via-point of L and the other is via-points of L and C.

Fig.3 shows the power flow chart for the conventional high frequency inverter reported as BHB-Boost Half Bridge [8], in which the circuit mechanism is compared and discussed with our strategy. The input power supply voltage is boosted in the half bridge inverter. After this operation, the high frequency ac power is obtained. After the energy of input power supply E is stored into L, the capacitor C is charged from power from L at switch turned-off. By means of this capacitor charge, the load R is supplied. The figure shows the flowchart of such operating mechanism, where there are three step power transmissions. On the other hand, for the proposed high frequency conversion, main transmission is performed by direct conversion from E to load, the other is a simple transmission way via single L or C. The number of conversion stage is much reduced. Consequently, the transmission efficiency can be expected as much improvement.

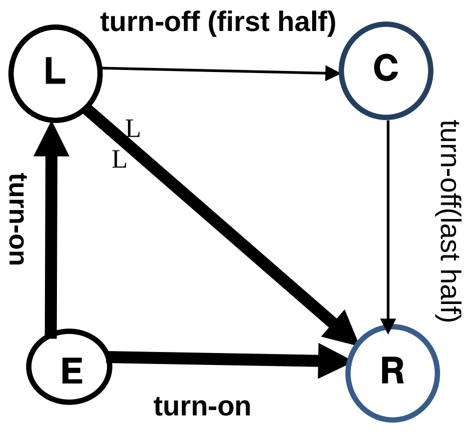


Figure 2. Power Flowchart of Novel Inverter.

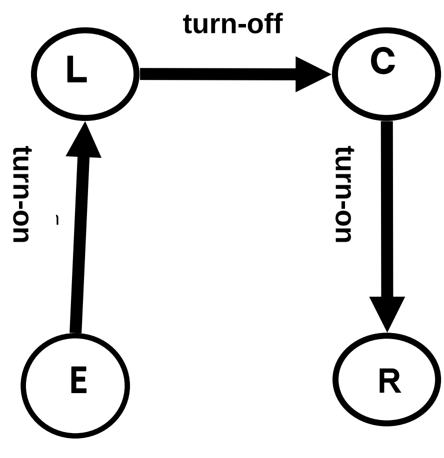


Figure 3. Power Flowchart of Half Bridge.

3 FURTHER DEVELOPMENT TOWARDS BUCK INVERTER

3.1 Operation and characteristic of buck inverter

For further development with minimum circuit component, another method can be derived as shown in Fig.4. By means of alternating switching of S_1 and S_2, the power is delivered to the load R, where inductor L could be connected in series to R. The sinusoidal wave could be obtained, if desired. In this paper, however, the rectangular wave is supposed. Unbalanced charge of C might be concerned, but it can be seen that balanced charge characteristic can be realized by following discussion. In steady state condition, when S_1 is turned on, the relationship is

$$E - vc(0) = Ri^{+}. \cdots\cdots\cdots\cdots (1)$$

When S_1 is turned off,

$$vc(0) = Ri^{-}$$

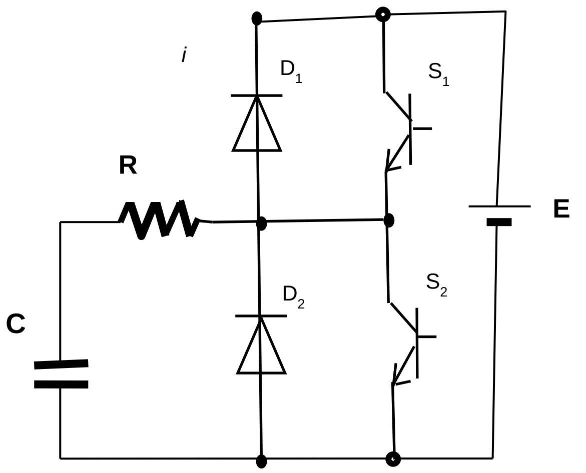


Figure 4. Circuit Configuration of Buck Inverter.

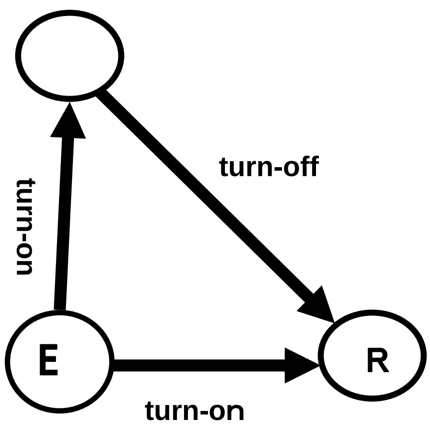


Figure 5. Power Flow of Buck Inv.

where $vc(0)$ is charged voltage of C,
i^{+} ; is charging current,
and i^{-} is discharging current.

$$\cdots\cdots\cdots\cdots (2)$$

・In steady state condition,

$i^{+} = i^{-}$, $vc(0) = E/2$

C is charged to half the supply voltage

$$\cdots\cdots\cdots\cdots (3)$$

・In transient condition,

when S_1 is turned on,

$$E - vc(t) = RC \times dvc(t)/dt. \cdots\cdots\cdots\cdots (4)$$

When S_1 is turned off

$$vc(t) = - RC \times dvc(t)/dt \cdots\cdots\cdots\cdots (5)$$

When the gradient of V_C, $dvc(t)/dt$ becomes equal, relationship of $E = vc(t)/2$ establishes and C is charged by $E/2$.

Fig.5 shows power flowchart. When S_1 is turned-on and S_2 is turned-off, the load R and C are supplied simultaneously. When S_1 is turned off and S_2 turned on, the R is supplied from power of C. In such a way, the half power from E is directly supplied to load R at S_1 turned on. This operation contributes to efficiency improvement that is fair advantageous. Fig.6 shows the flowchart of conventional BHB inverter for comparison [8]. For half bridge, C is connected in series with supplied power, image of sequential power transmission may be occurred. But actually, the circuit is changed by two steps. Thus, efficiency consideration should be taken into account a little.

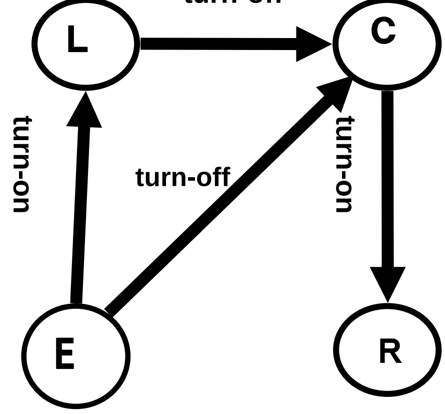


Figure 6. Flowchart of Conventional BHB Inverter. [10].

4 COMPARISON OF ESTIMATED TRANSMISSION EFFICIENCY

4.1 Local transmission efficiency

A. *Proposed Buck Boost Inverter*

According to the value of inductor, the by-passed load current to the capacitor is varied and the efficiency becomes also varied. The influence due to inductor ripple is considered and the operation is analyzed.

・ *L is sufficiently large* **;** The by-passed current through C becomes much reduced, in which conversion efficiency is a little improved. In order to get hold of conception of efficiency value, it is assumed that efficiency between single stage is, for example $\eta = 90\%$. Thus,

$$E \rightarrow R(\eta \times \tau_{on} = 45\%), E \rightarrow L(\eta \times \tau_{on} = 45\%), L \rightarrow R(\eta \times \tau_{off} \times \eta = 40.5\%) \quad \cdots (6)$$

Under consideration of power flowchart in above Fig.5, the total efficiency can be obtained as follows,

$$(\eta \times \tau_{on} = 45\%) + (\eta \times \tau_{off} \times \eta = 40.5\%) = \underline{85.5} \quad \cdots (7)$$

In equation, the total efficiency can be obtained by summation of each value during τ_{on} and τ_{off} period.

・*L is not sufficiently large.* **;** The power through C is dependent on the current ripple relative to average load current I_o. For example of assumption, the relative value will be given by $R/(L4f_o) = 1/2$. Thus, the conversion efficiency can be calculated. The power transmission through C is assumed to be constant, $\alpha_C = 1/8$. The direct transmission to R is the remainder, $\alpha_R = 7/8$. In such way, the whole transmission is performed as follows;

$$E \rightarrow R(\eta \times \tau_{on} = 45\%), E \rightarrow L(\eta \times \tau_{on} = 45\%), L \rightarrow R(\eta \times \tau_{off} \times \alpha_R \times \eta = 35.4\%), L \rightarrow C(\eta \times \tau_{off} \times \alpha_C \times \eta = 5.1\%), C \rightarrow R(\eta \times \tau_{off} \times \alpha_C \times \eta \times \eta = 4.6\%) \quad \cdots (8)$$

To be put in order, the following total efficiency can be obtained, that is.

$$(\eta \times \tau_{on} = 45\%) + (\eta \times \tau_{off} \times \alpha_R \times \eta = 35.4\%) + (\eta \times \tau_{off} \times \alpha_C \times \eta \times \eta = 4.6\%) = 8\underline{4.98\%} \quad \cdots (9)$$

B. *Boost Half Bridge-BHB type* [8];

・When L is not large ;

the compensated capacitor current includes the ripple, whose value is assumed to be the same as the above example. The power transmission ratio through the upper capacitor is assumed to be constant $\alpha_C = 1/8$. The direct transmission root through L, C_2 to R is the remainder, $\alpha_R = 7/8$. Thus,

$$E \rightarrow L(\eta \times \tau_{on} = 45\%), L \rightarrow C_2 \rightarrow R(\eta \times \tau_{off\text{-}on} \times \alpha_R \times \eta \times \eta = 31.89\%), L \rightarrow C_1 \rightarrow R(\eta \times \tau_{off} \times \alpha_C \times \eta \times \eta = 4.55\%) \quad \cdots (10)$$

where $\tau_{off\text{-}on}$ means relative turn-on period and turn-off period represented by $\tau_{off\text{-}on} = 1/2$.

・*When L is sufficiently large* **;** The deviated current through upper C is almost zero. The efficiency is calculated as follows;

$$E \rightarrow L(\eta \times \tau_{on} = 45\%), L \rightarrow C(\eta \times \tau_{off} \times \eta = 40.5\%), C \rightarrow R(\eta \times \tau_{on} \times \eta \times \eta = 36.45\%), E \rightarrow R(\eta \times \tau_{off} = 45\%) \quad \cdots (11)$$

The total efficiency is given by

$$(\eta \times \tau_{on} \times \eta \times \eta = 36.45\%) + (\eta \times \tau_{off} = 45\%) = \underline{81.5\%} \quad \cdots (12)$$

where $\tau_{off\text{-}on}$ means relative turn-on period and turn-off period represented by $\tau_{off\text{-}on} = 1/2$.

To be put in order, the following total efficiency can be obtained.

$$(\eta \times \tau_{on} = 45\%) + (\eta \times \tau_{off\text{-}on} \times \alpha_R \times \eta \times \eta = 31.8\%) + \eta \times \tau_{off} \times \alpha_C \times \eta \times \eta = 4.5\%) = 81.3\% \quad \cdots (13)$$

C. *Buck inverter type* ; Each transmission efficiency is given by the similar manner as before.

$$E \rightarrow R(\eta \times \tau_{on} = 45\%), E \rightarrow C(\eta \times \tau_{on} = 45\%), C \rightarrow R(\eta \times \tau_{off} \times \eta = 40.5\%). \quad \cdots (14)$$

The total efficiency is <u>85.5 %</u>

D. *Conventional Half bridge inverter*;

Firstly, switch is turned-on, the power is transmitted as follows;

E→R($\eta\times\tau_{on}$=45%), E→C_1($\eta\times\tau_{on}$=45%), C_2→R($\eta\times\tau_{off}\times\eta$ = 40.5%).. ･････････････(15)

By the next switching, the operation of transmission is repeated.

E→R ($\eta\times\tau_{on}$=45%), E→C_2($\eta\times\tau_{on}$=45%), C_2→R($\eta\times\tau_{off}\times\eta$ = 40.5%). ･････････････(16)

The total efficiency becomes 85.5%.

E. Comparison of Characteristics among Variable Converter

Table 1 Characteristics of Variable Converters.

	Eff %	Num.	Load V	Max.curren
Buck-Boost Inv	85.5	8	*E*	*I*
(with ripple 1/2)	(85.0)	(8)	(*E*)	(*I*)
Boost-Half-Bridge	81.5	9	*E*	*I*
Buck Inverter	85.5	7	*E*/2	*I** 2
Half Bridge Inv.	85.5	8	*E*/2	*I** 2

Table 1 shows characteristics mainly for conversion efficiency among various converters. Two converters on the upper two stages and on the lower two stages are analogous characteristics, respectively.

Firstly, as comparing two converters, Buck-boost Inverter and BHB [8] on upper stage, both inverters are having favorable feature of high load voltage. The maximum device current for BHB becomes double that is fairly disadvantage. The number of devices of the proposed Buck-boost Inv. is decreased from nine to eight, which brings the improved efficiency by a few percent. Secondly, on the bottom stage by two inverters, the disadvantage is that the supplied voltage *E* is given by 1/2, while the current is double . This feature brings shortage of efficiency. For withstand current of device, however, the increased current over load current does not flow. For buck inverter, as compared to conventional Half Bridge Inverter, the number of devices is decreased by unity.

5. DETAILED OPERATIONAL DISCUSSION FOR PROPOSED BUCK INVERTER

In advance of confirmation in the experiment by circuit simulation, the circuit performance is analyzed in detail by using operating circuits. The operation starts from S_1 turning-on in Fig.7.

・Period I

When S_1 is turned-on, conduction to the load starts. At the same time, the charge toward the capacitor begins. The supplied power from E is $E\times i$. Consequently, the circuit differential equation is given by

$$E = L\frac{di}{dt} + Ri + \int i/C\, dt \quad \cdots\cdots(17)$$

In the right side equations, the front two terms are the power which burdens the load and the last term is for the capacitor C charging. When the switch S_1 is turn-off, this period comes to an end.

・Period II

When S_1 is turned-off. Due to the stored energy of inductive load, the current is continued to flow where current flow is supported through D_2. That is, the current is commutating to this path and continues to flow into the capacitor. This energy is supplied from the load of inductive component.

・Period III

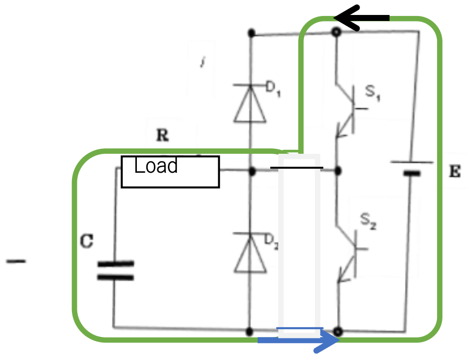
After the energy of L is discharged, the current becomes zero. According to the polarity of capacitor voltage, the current begins to flow in that direction. That is, at the end of period I, S_1 is turned-off and S_2 is turned-on, according to the polarity of capacitor voltage, the current flowing starts and the load is supplied. The circuit equation is as follows;

・Period IV

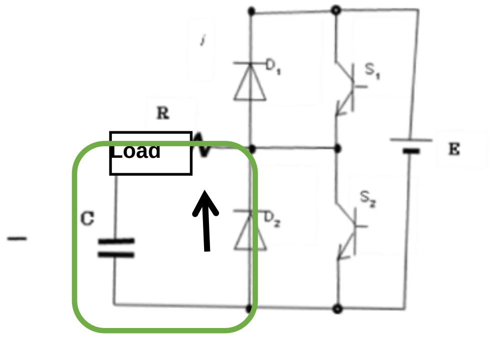
When S_2 is turned-off and S_1 is turned-on, flow is reversed ones during this period when the D_1 is conducted. Namely, due to the stored energy of the inductive load the operation is established. According to the load of inductive component, the energy is returned to the power supply and this period comes to an end. The power regenerative operation is only this period. In this operating circuit, even if there is only one capacitor, that is, even if there is no another capacitor, usual operation can be performed successfully. As a result, the circuit component is reduced by unity. That is this feature is remarkable characteristic. The stored energy of L and C is regenerated towards E and supplied to R as follows.

$$E_C - E = L\frac{di}{dt} + Ri \quad \cdots\cdots\cdots\cdots(18)$$

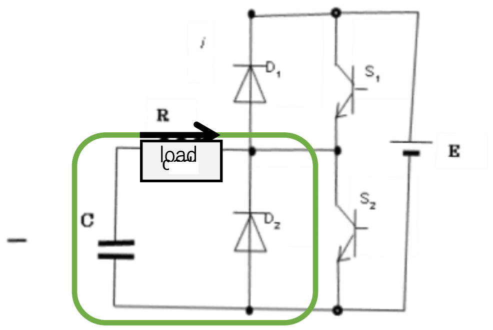
In usual half bridge, the regenerating operation towards supply does not occurs, so this operation characteristic is disadvantageous.



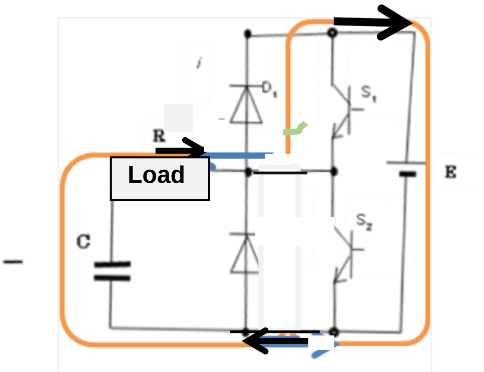
(a) Period I



(b) Period II



(c) Period III



(d) Period IV

Figure 7. Operational Circuit of Buck Inverter.

6. EXPERIMENTAL CONFIRMATION BY USING CIRCUIT SOFTWARE, PSPICE

Fig.7 shows schematic circuit configuration, constructed by circuit software by PSpice. The corresponding circuit is shown as proposed inverter for the first mentioned in Fig,1. The transistor switches are represented by devised pulse generators, operating switching period is shifted half cycle each other. When the switching is turned on, the generator voltage becomes zero. When the switch is turned off, the generator becomes high voltage. At that time, the current is blocked to flow. The dammy resistors play the role to keep the execution of the calculation of differential equations in the software. Fig.8 shows the simulated result by using simulator of Fig.7. Each result shows anticipated ones.

6 CONCLUSIONS

The paper is presented and confirmed by circuit software, PSpice, whose idea is obtained from unified inverter circuit constructed by chopper and inverter circuit. The number of the conventional corresponding circuit configuration is totally ten, while for the proposed construction, the number is eight. This result is the reason why the proposed inverter is called as minimum circuit construction. In parallel load method, which can be developed to dc to dc converter, as the number of conversion stages is reduced satisfactorily, an improved efficiency can be achieved. Finally, as looking at the whole view compared to the usual PVG having large scale inverter. The characteristic may be, however, a little deteriorated. Because of providing towards limited area power supply, quality of electric power is fairly permitted. The authors have been researching about superb photovoltaic power generation system for medical facilities. In such place, employing electrical equipment is strictly required in the standard based on regulation according to like “Japan Industry Standard” [9,10], where requirement for basic safety and

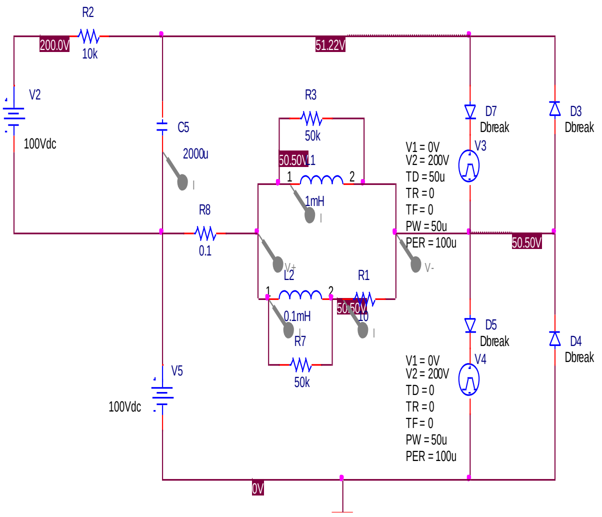


Figure 7. An Example of Schematic Circuit in Simulator, PSpice.

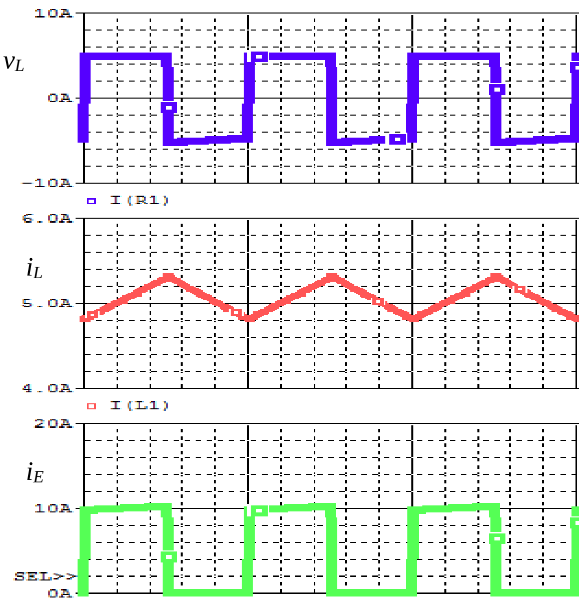


Figure 8. Simulated Waveforms of Proposed Jnverter.

essential performance for the medical equipment, is dictated. The important degree of emergency power supply is varied according to its treatment for medical electrical equipment like life sustainable system, operating room light maintenance, etc. [11]. For example, in artificial respiration equipment or patient monitor, if no battery installation system is adapted, such power supply system is not permitted. In optimum design specification of PV power generation system, adaptive installation may be more efficient.

In the near future, with a spread of ultra-large-capacity and ultra-high-speed internet communication system, remote control surgery like in remote island may be realized, it is said. In such a case, even more reliable power supply system will be important.

ACKNOWLEDGEMENTS

This research is mostly supported by a grant of Research Institute for Life and Health Sciences of Chubu University - Short Term Research Project. We would like to express our appreciation to who it may concern about this project.

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