Research on Small Power Conditioners for Photovoltaic Power Generation Installed on Public Facilities

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The Asian Conference on Sustainability, Energy and the Environment 2019
Official Conference Proceedings

Abstract
Photovoltaic–PV power generations has been spread around the world. In such system, power conditioners that is used for conversion from dc to ac and is much important, so it has been studied by many researchers. In addition to usual utilization, such PV generation is often supplied for the time of disaster. Usually such solar panels having limited power are almost installed on top of the roof of the building and the like. In such applications, some medical institutions or some public facilities have fairly desire to keep such kind of power. For almost electrical equipment using in such medical facilities, even instantaneous interruption could never be permitted. The generating power in a case is quite limited, so the system construction should balance the reduced power. Thus, it is necessary to improve the construction toward simple one. In this research, in a process to study such system, the simple and concise power converters have been found by the authors. Considering rather narrow space of installation, the system constructions should be compact. The circuit which gratifies their operating characteristic is presented. In a series of the study, this time, dc to ac converter is analytically discussed about circuit construction as a novel circuit converter. This power conditioner is analytically discussed and the superior characteristic is presented. Unsatisfactory characteristic is improved by using some novel techniques.

Keywords: Veranda solar, PV power generation, Power conditioners, PVS, Solar panel, Photovoltaic power generation, Power converter, Inverter, Small power generation

Introduction

Utility-interactive photovoltaic power generations have been realized and accepted widely. Various researches about power conditioners that interface between photovoltaic arrays and ac utility system have been also utilized. Such innovative conditioning systems have been also discussed. On the other hand, in the latest medical equipment, the development of the structural function in the operating system is remarkable. The endoscopic surgery including surgical robot and the catheter intervention have been applied, so such remarkable operating techniques have been developed with like robotic operating room and hybrid operating room[1,2]. For almost electrical equipment using in such medical facilities, even instantaneous interruption could never be permitted. In general, large scale interruptible power supplies installed by generators and batteries are provided. In such system, however, the system scale becomes so large which is accompanied by high cost. The power conditioners-PCS including inverter have been considered in various systems so far [3-5].

In the actual application, such solar panel is installed on top of the roof of the building or limited space. Some users of public or medical facilities are having a fairly strong desire to install such interruptible power supply using natural energy generation with low cost. In this study, in order to give the reply, a simple and concise photovoltaic power generation system is to be considered and discussed. Considering fair reduced generation power and limited space of installation, the system constructions should be simple and concise. In this research, the circuit which gratified their wishes are presented. System circuit and their sophisticated construction will be presented and analyzed. 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. Thus, it is required to obtain even more low cost PCS. In an extremely lower capacity PCS like proposed one, a way of handling would be different compared to conventional ones. In such case of reduced generating power, quantities of regenerating power to the power system would be small, where another mitigated regulation or deregulation would be approved. Thus, in such photovoltaic power generation systems, there are so many subjects to be resolved.

Half Bridge Circuit Configuration and its Outline

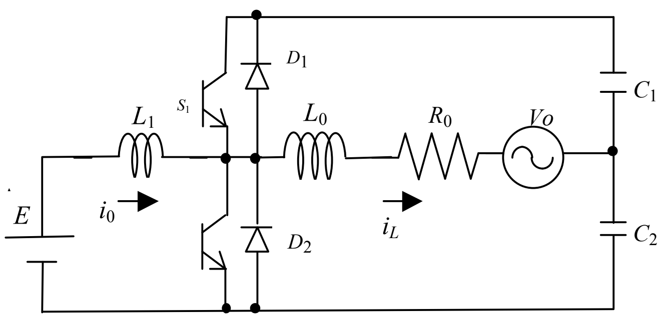


Fig.1. Proposed PCS constructed by half bridge.

Fig.1 shows an example of proposed PCS (Power Conditioners) which is constructed by the half bridge construction [6,7]. The single phase or three phase constructions using full-bridge circuit are possible for the PCS, but the operation is begun to discuss from fundamental half-bridge circuit. In the conventional inverter, the boosted output voltage from boost converter is given to the dc link voltage terminal as usual connection. In the proposed PCS, however, the output voltage is given to the midpoint of inverter leg through accompanied inductor as shown.

For the switches S_1 and S_2 which are operating for normal load of L_o and R_o or ac power source V_o of utility interactive operation, the regular signals are given as usual, where L_o is line inductance R_o is line resistance. In this control strategy, for example, of natural sampling method (triangular-sinusoidal wave comparison method), as the average turned-on ratio is given by $\alpha = 0.5$, the dc link voltage of inverter is boosted by two times which can be calculated from the theory in boost converter. As a result, the input dc power supply voltage can be boosted by two times. In such a way, $2E$ voltage can be obtained across the inverter capacitors, where E is input dc supply voltage. S_2 plays also a role of the function of boost converter switches. By means of using merely single inverter construction, a novel inverter construction having boosted voltage capability can be obtained. The dc link voltage of inverter is given by

$$V_I = E/(1 - d) \tag{1}$$

where d : the average value of duty ratio

E : Input power supply voltage.

Assuming the sinusoidal and triangular wave comparison method, regardless of the modulation factor (ratio of sinusoidal amplitude / triangular amplitude), average value of conduction factor becomes $d = 0.5$. Consequently, inverter dc link voltage becomes $V_I=2E$. The voltage V_L across L is given by subtracting input voltage from point A voltage, that is

$$V_A = V_L + E \tag{2}$$

In the load circuit,

$$V_A = V_o + E \tag{3}$$

where V_o is load voltage including line inductance and resistance voltage.

Consequently,

$$V_L = V_o \tag{4}$$

It can be seen that applied voltage across the input inductor becomes fairly large, so subsequent current becomes also large, whose value should be suppressed by input inductance itself. The applied voltage frequency is lower commercial one, so in order to suppress the input current, input inductance should be selected as a little increase. That characteristic is considered to be a weakness. In order to improve that characteristic, a novel control strategy is proposed.

Actual Application to Proposed Power Conditioner

(A) Buck converter compensation

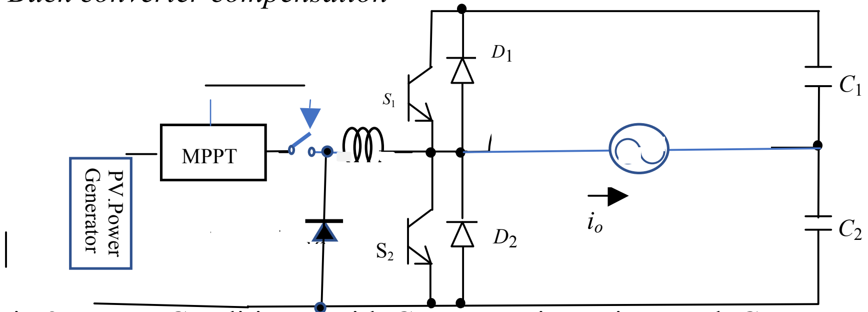


Fig.2. Power Conditioner with Compensation using Buck Converter.

Fig.2 shows the power conditioner for the purpose to improve the input current characteristic. By using of compensation due to buck converter, the deteriorated operation can be improved. In the actual application of usual PV generation, it is necessary to employ the MPPT(Maximum Power Point Tracker). In a case of Fig.2, by means of buck converter, maximum power point operation is executed and can be kept as constant power point operation at maximum power point. In this operation, switching current of buck converter is kept almost constant current during short period as just like the current source type operation. As a matter of course, according to changing of the amount of solar radiation, the controlled current of buck converter is also varied. In the short term, however, input current can be kept constant, so it can be called this converter operation as the current source converter.

In the output side inverter, the switching operation of S_1 and S_2 is executed by following equation.

$$V_o = aE\times\sin\omega t \qquad (5)$$

where a is modulation index.

According to the execution of natural sampling modulation, each pulse width is given by the value of this equation. Even if the modulation index a is varied, dc link voltage can be kept constant. The reason can be resolved as following discussion. In the half bridge inverter, when the modulation index is given by zero, the output waveform is given by pure rectangular waveform having equi-pulse width. The duty factor of switch S_2 is $d = 0.5$. As a result, the output dc link voltage is

$$V_o = 1/(1\text{-}d) = 2.0\times E \qquad (6)$$

When the sinusoidal waveform is required to solve, the duty factor d is given by

$$d_{sin} = d + a\sin\omega t \qquad (7)$$

By means of this equation, output pulse width is obtained. The dc link voltage is resolved by means of this average value. That is,

$$D_{sin} = (1/2\pi)\int d_{sin}\, \mathrm{d}\omega t$$
$$= (1/2\pi)\int (d + a\sin\omega t)\, \mathrm{d}\omega t \qquad (8)$$

Consequently, because of

$$\int a\sin\omega t)\, \mathrm{d}\omega t = 0 \qquad (9),$$

following result can be obtained as

$$D_{sin} = d. \qquad (10)$$

Consequently, dc link voltage becomes,

$$E_{dc} = E/(1\text{-}d) = 2E, \qquad (11)$$

in a case of d=1/2.

In a synchronous carrier of S_1 , S_2 and S_M, there are two types timing. For first case of (a), one is that S_M is turned-on when S_2 turned-on. The second case of (b) is that S_M is turned-on when S_2 turned-off.

- (a) For S_M-on and S_2-on, Power injection mode,
- (b) for S_M-on and S_2-off, Discharge boost mode,
- (c) for S_M-off and S_2-on, Power circulating mode,
- (d) for S_M-off and S_2-off, Regenerating mode.

In a case of (a), PV power is directly injected into input inductor L_1. This operation is the same one compared to the usual chopper power injection. In a case of (b), the stored charge during case (a) is discharged toward capacitor C_1 and C_2. Usually PV voltage is boosted by this operation. In a case of (c), because of S_M-off state, PV power is not connected and not supplied, so the storage power is circulating through L_1, S_2 and D_3. In a case of (d), the storage energy of inductor is regenerated towards capacitor C_1 and C_2. By means of this operation, the current is toward reducing.

Usual weakness that had better improve is to suppress the input current variation, especially increase due to sinusoidal waveform. Such deterioration can be modified above mentioned circuit performance. Such operation can be adapted to improve. For a case of (a), S_M-on and S_2-on, power injection mode operation, the modulation signal is modified. The duty factor d is given by

$$d_{sin} = d + a \sin\omega t \qquad (12)$$

The second term $a\sin\omega t$ is varied from zero to a. Due to this over modulation and from boost voltage theory, the input current is fairly increase. Instead of this modulation, another modulation due to S_M operation is employed.

By means of this equation, output pulse width is obtained. The dc link voltage is resolved by means of this average value. That is,

$$Dsin = d + \left(\frac{1}{2\pi}\right)\left(\int_0^{\pi} a\sin\omega t\, d\omega t + \int_{\pi}^{2\pi} a\sin\omega t\, d\omega t\right) \qquad (13)$$

By assuming $a = 1$, $d = 0.5$ 、 and from 0 to π, the modulation index is adapted as d = 0.5, so in the right side, second term becomes,

$$\int_0^{\pi} a\sin\omega t d\omega t = 0 \qquad (14)$$

As a result,

$D_{sin} = 0.5 - (1/\pi) = 0.182$ (15)

From boosting voltage theory, that is

$E_{link} = 1.22$ (16)

If you want to increase the dc link voltage, instead of Eq.(A) where M is zero, following Equation where M is finite value from zero to unity.

$$\int_0^{\pi} M\, a\sin\omega t\, d\omega t \qquad (17)$$

(B) Boost converter compensation

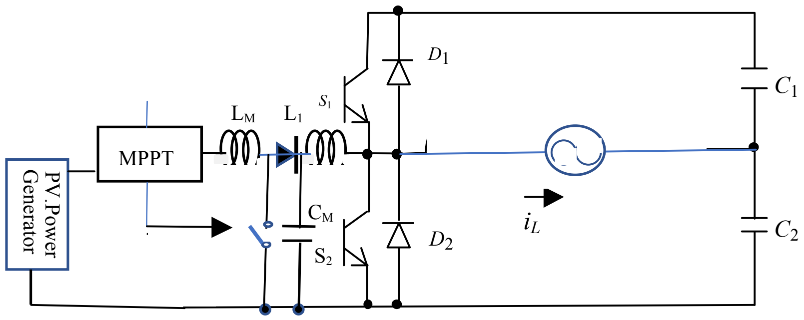


Fig.3. Power Conditioner with Compensation using Boost Converter.

Fig.3 shows the power conditioner for the purpose to improve the characteristic. It is different from just mentioned buck converter method, by using boost converter, the deteriorated operation can be improved. In the actual application of usual PV generation, it is necessary to employ the MPPT. In a case of Fig.3, by means of boost converter, maximum power point operation is executed and can be kept as constant point operation at maximum power point In this operation, switching current of boost converter is kept almost constant current during short period as just like the current source type operation. As a matter of course, according to changing of the amount of solar radiation, the controlled current of buck converter is also varied. In the short term, however, input current can be kept constant, so it can be called this converter operation as the current source converter.

・(a) For S_M-off and S_2-on, Power injection mode.
When S_M is turned-off and S_2 is turned-on, power is injected into a series inductor of L_M and L_2.
・(b) for S_M-off and S_2-off, Discharge boost mode,
S_2 is turned-off and S_M is turned-off, power is delivered toward a series capacitor C_1 and C_2. The link voltage is going to increase.
・(c) for S_M-on and S_2-on, Power circulating mode,
When i_M is larger than i_{L1}, the input current is circulating, so that current is not increase.
・(d) for S_M-on and S_2-off, Regenerating mode.
S_M current increases and i_{L1} current is regenerating to dc link circuit of capacitor.

The function of capacitor C_M is as follows; If the current i_{LM} is larger than i_{L1} when the switch S_M is turned-off, in the usual operation, commutation from i_{LM} to i_{L1} cannot be performed satisfactorily. At that time excess energy is temporarily stored in the filter capacitor C_M. After that the commutation from i_{LM} to i_{L1} is completed.

Discussion will start from the initial modulation definition. Photovoltaic power is obtained by dc power from solar panel, so it is required to convert into the ac power for actual applications. At the first stage, that power is boosted to adequate voltage level, so the power is processed by boost converter. According that procedure, the power is converted to ac power. That control signal is obtained as PWM signal. The representative signal processing method is given

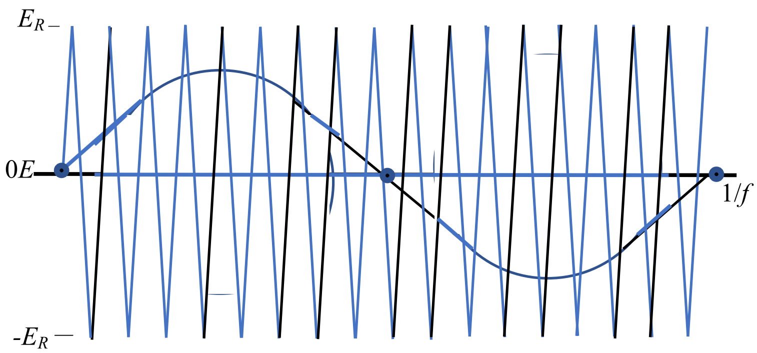
By natural sampling modulation. The sinusoidal waveform is given by

$$e_s = E_s \sin\omega t, \qquad (18).$$

$e_r = E_R$ triωt, (19).
where formula symbol "tri" means triangular waveform shown in Fig.3. In Fig.3, PWM signal eo is given by following procedure.
When $e_s > e_r$, then

$$e_o = E \qquad (20).$$

and when $e_s < e_r$, then
$e_o = -E$. (21).
Assume that the switching frequency is much high, then the output waveform can be obtained as follows; In the figure, on the upper side relative to zero axis,
$e_{up} = E/2 + aE/2 \sin\omega t$ (22).
$e_{down} = E/2 - aE/2 \sin\omega t$ (23).
where a is modulation factor, that is
$a = E_s/E_R$. (24)



Summation of these equations gives subsequent equation, that is,

e_{up} - e_{down} = $aE\sin\omega t$ (25).

When the load is operating in the sinusoidal waveform with commercial frequency, the fundamental performance is a little different compared to high frequency inverter to above mentioned. Consequently, the auxiliary inductor voltage is also different. The voltage of such inductor can be obtained as follows;

When S_2 is turned-on, applied voltage across the inductor is

$E_L = aE\sin\omega t$. (26).

When S_2 is turned-off, the voltage of

$e_L = E_C - aF\sin\omega t$ (27).

This voltage is applied across the auxiliary inductor. Actually, the value of voltage is varying across the half period, so it is necessary to calculate the average value. By means of this value, the necessary magnetic flux of inductor can be calculated. That is,

$E_{oave} = \int aE\sin\omega t\,dt/\pi = 2aE/\pi$ (28)

$= \int(E_C - aF\sin\omega t\,dt$ (29).

Assume that $E_C = F$, then

$a = \pi/4 = 0.785$ (30).

The modulation factor has an upper limit value as shown. Beyond of this value, the modulation factor could not be exceeded.

Conclusions

In a series of research as "Pursuit of ideal power conditioners", an achievements can be attained on the process in the considering. For as one of those, the improved converter is proposed and analytically discussed for high performance whose idea is obtained from MPPT of the photovoltaic power generation system. In the first version which can realize by buck chopper, in which the boost chopper could be applied as suppression of input current. Some analytical characteristics can be realized. In the second version, by boost chopper of MPPT, input current chatacteristics could be improved. The original strategy of these converters has been proposed by the authors. The most important characteristic is compact and concise construction and is adequate one for small power converter.

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 like "Japan Industry Standard" [13], where the standard of medical electrical equipment is determined. In the standard, that is in part 1: General requirements for basic safety and essential performance is dictated. The important degree of emergency power supply for medical electrical equipment is varied according to its treatment for medical electrical equipment like life sustainable system, operating room light maintenance [14]. 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 required.

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 possible, it is said. In such a case, even more reliable power supply system is important. In the important ME equipment,

In the proposed converter for load voltage, the supply voltage can be applied directly as advantage. The maximum, current of component is double of load current as disadvantage. For proposed converter, the number of component is reduced which brings efficiency improvement。 In lower two stages, the load voltage is reduced to half of the supply voltage as disadvantage, but the load current does not flow over load current. Comparing both inverters, the number of component of Buck Inverter is reduced by unity., 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 with the usual half bridge construction, one of double supply capacitors is replaced by dc power supply from regular position, that is an interesting appearance.

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.

The paper is proposed and presented whose idea is obtained from unified inverter circuit constructed by chopper and inverter circuit. In the first version which can realize sinusoidal wave, the number of the circuit construction can be made minimum. 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 with the usual half bridge construction, one of double supply capacitors is replaced by dc power supply from regular position, that is an interesting appearance.

Through this research, an adequate and feasible circuit construction as simple and concise power conditioners have been presented and analytically discussed.
The feature of proposed PCS systems is to pursue a lower cost one including the

construction cost. According to reducing the capacity, the cost of solar panel is reducing in proportion. The cost of PCS, however, is not reduced in proportion to capacity. A novel PCS suitable for small capacity is proposed. This system can be performed at minimum wiring work at construction.

By means of Feed-in Tariff, the PV power generation has been developed widely. It is very important that the end user feels an economic merit which brings wide spread of PV power generation like as social phenomenon. The most important thing is that the cost is lower than charge of electric company.

In additional important thing, the visualization tool could be mentioned, in which the generating power can be easily viewed like handy smart phone. By means of this tool, if the power can be measured as a “negawatt”, economical merit can be realized and confirmed by viewing. If our visualization tool is realized with “Trade of Negawatt”, which is promoted by Ministry of Economy, Trade and Industry. The veranda solar could be widely spread.

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