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a new method of maximum power point tracking (MPPT) of photovoltaic (PV) cells using impedance adaption by Ripple correlation control (RCC).

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Abstract: In this paper , we are likely to introduce a new method of tracking maximum power point of PV arrays . the relationship between arrays output power and load impedance enables us to provide suitable adaption between load impedance and internal impedance of arrays and find the optimum operating point to receive maximum available power of PV arrays . a boost convertor is connected between arrays and load to adapt load impedance to PV internal impedance . Ripple correlation control (RCC) , is used as a basic law to correlate load impedance and power Ripples in order to compute duty ratio of switching devices to maximize PV output power via adapting load and PV internal impedance .

Keywords: photovoltaic , maximum power point , ripple correlation control , impedance adaption , boost convertor.

I. Introduction

the ever increasing demand for electrical energy and concerns about world oil crisis , has led governments to renewable energy sources . Photovoltaic (PV) energy is the most important and easiest one to obtain. beside it's pollution free and inexhaustible. Nowadays photovoltaic cells are widely used all around the world . photovoltaic cells are manufactured in various sizes . It's very important to receive maximum available power from PV arrays to improve output efficiency. there are many papers dealing with Maximum power point tracking (MPPT) of PV arrays . some papers employed hill climbing method [1] and used slope of power versus voltage to track maximum power point very rapidly . in many papers perturbation and observation (P&O) [1,2,3] has been introduced as the most conventional and easiest method of tracking maximum power point of PV arrays via increasing or decreasing the duty ratio of on-state of switching device . in another paper , an interesting method is presented based on Fibonacci search algorithm [4] to realize simple control system to track the real maximum power point even under non-uniform or for rapidly changing insulation condition . this Fibonacci search technique was modified in order to apply to time variant P-V characteristics of the PV array.

Artificial neural networks [5] lead us to a new method of tracking maximum power point in MPPT system and it's robustness and insensitivity to the intermediate weather condition is enhanced.

photovoltaic systems can also be used in combination with other energy sources . for example a PV system can be combined with wind turbine to form a hybrid renewable generation system [6] . PV arrays usually supply a series of batteries to store generated electric energy .

photovoltaic generation systems can either be grid connected [7-8] or stand alone [9] . the former type is applied for large scale PV plants with significant nominal output power connected to infinite bus of power systems to improve system stability .

in most papers , the nonlinear voltage-current characteristic of arrays output is presented and corresponding power-voltage or power-current curves are plotted .

a new method of tracking maximum power point of PV arrays based on power versus impedance (P-Z_L) characteristics of PV output is presented in this paper . a boost convertor is connected between PV arrays and load (battery box) to adapt load impedance to arrays internal impedance . in this case , load impedance consists of a DC value plus a Ripple component . Ripple correlation control (RCC) is used as a basic law to correlate load impedance and track the optimum load impedance (Z_L) at which maximum power point of PV occurs .

II. Proposed MPPT method

Fig.1 shows the proposed PV system consisting of series-parallel PV arrays , a boost convertor and a load containing several batteries to store Generated electric energy . the parasitic capacitance of Array has little effects , so its modeled into the convertor capacitor , C . z_l is the load impedance and is the equivalent impedance of battery box and boost convertor.

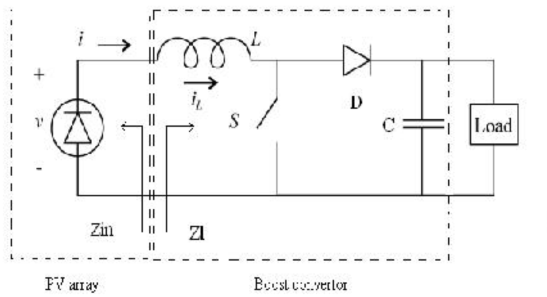

Fig.1 PV array connected to a boost convertor and battery loads.

the average arrays equivalent voltage and output power versus average load impedance curves are shown in Fig's 2 and 3 respectively .

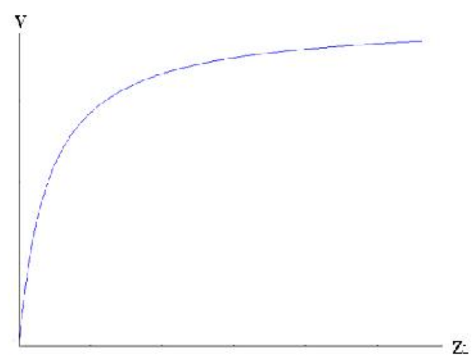

Fig.2 voltage versus average Load impedance (Z_L) of typical PV system.

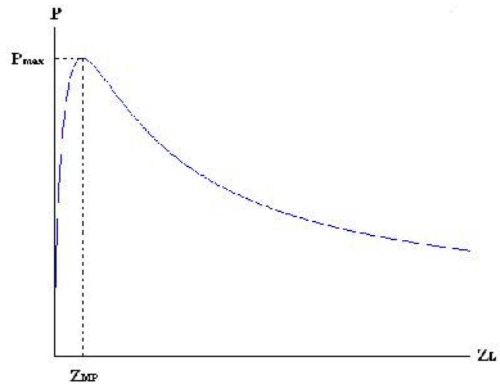

Fig.3 : the average power versus average load impedance curve.

fig.4 shows a comparative view of both curves in a single diagram . the load impedance , z_l , is adjusted by appropriate switching of switch S to maximize the average output power of PV array . in the case of boost convertor , z_L comprises of a dc value , Z_L and a ripple component , $\tilde{z}_L$ (fig.5) . this is also the case for PV output voltage (v) , means v comprises a dc value V and a ripple component $\tilde{v}$. at a given temperature and irradiance z_L is adjusted and the power flow is $p=v^2/z_L$. this power is composed of a dc value P and a Ripple component $\tilde{p}$. as irradiance and temperature vary , the P-Z curve shifts in disparate direction . in this paper , the goal is to correlate load impedance , z_L to track Z_{MP} to receive maximum available power from PV arrays . as you see in fig.4 , to receive maximum PV output power , following condition must be provided:

$$Z_{in} = Z_{MP} = \frac{1}{T}\int \frac{v(t)}{i(t)}dt \qquad (1)$$

Where

Z_{in} is the internal impedance of PV arrays.

T is the frequency period of boost convertor.

V(t) and i(t) are PV output voltage and current respectively .

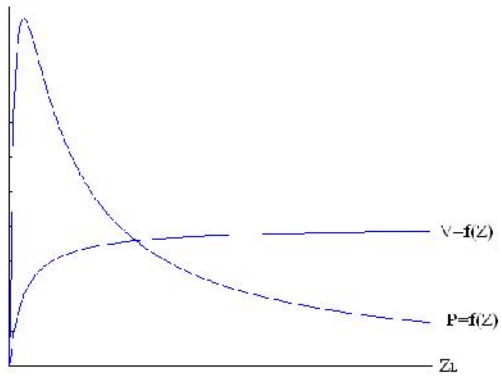

Fig.4 : a comparative view of power and voltage versus average load impedance.

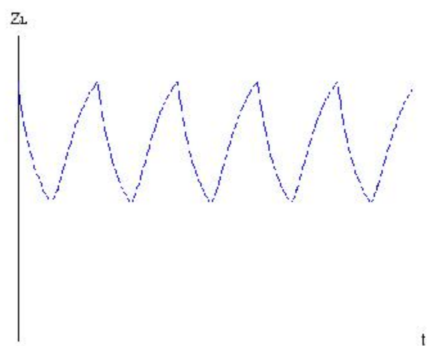

Fig.5 : load impedance Ripples of typical PV system with boost convertor.

When this condition achieves , it means that z_l has tracked the maximum PV power . moving along the V-Z curve shows that to receive the maximum PV power , PV operating voltage has to be adjusted to opperate around knee point of curve .

III. Ripple correlation control

To track maximum power point of PV arrays , we need to correlate the load impedance z_l and power p in order to determine whether z_l is above or below Z_{MP} . whenever z_l equals Z_{MP} , average load impedance will be equal to internal impedance of PV arrays . therein the goal is to find and adjust duty ratio (D)of switch S of boost convertor to provide a good adaption between load impedance and arrays internal impedance . the simplest approach is to find the optimal set point when the derivative of power to impedance (dp/dz_L) is zero (2) and then make an integrand to obtain duty ratio (D) but the integrand of (2) is't generally a signal that is available in real boost convertor .

$$D = \int \frac{dp}{dZ_l} dt \qquad (2)$$

As previously mentioned The practical approach is to find whether Z_L is below or above Z_{MP} in P-Z_L curve , we have to first consider changes in power and load impedance . with assumption that PV internal capacitance is modeled into boost capacitance C , following equation (3) is presented . according to (3) , when the product of time derivative of z_L (dz_L/dt) and the time derivative of power (dp/dt) is positive , the impedance ripple imposed along the curve leads to an in-phase power ripple and z_L is below Z_{MP} . if this product is negative , this means that z_L is above Z_{MP} and the impedance and power ripples are out of phase .

$$\begin{aligned} \frac{dz_L}{dt}\frac{dp}{dt} > 0 \rightarrow Z_L < Z_{MP} \\ \frac{dz_L}{dt}\frac{dp}{dt} < 0 \rightarrow Z_L > Z_{MP} \end{aligned} \qquad (3)$$

Equation (3) is a fundamental RCC law to compute duty ratio of switch S to maximize PV output power . expanding (3) yields equation (4) as follows:

$$D = k\int \frac{dp}{dt}.\frac{dz_L}{dt}dt \qquad (4)$$

Where D is the duty ratio of switch S of boost convertor and k is a constant positive gain . z_L increases or decreases when the duty ratio (D) decreases or increases . so adjusting D should provide correct movement of z_L.

Sign information about derivatives terms can be used instead of derivative information in RCC mentioned in previous section . for example , one useful control law is :

$$D = k\int sign(\frac{dz_L}{dt}).sign(\frac{dp}{dt})dt \qquad (5)$$

In (5) the ripple caused by differentiation is clipped by the sign function because this is easily done via using simple electronic and logic devices such as op-amp circuits or other inexpensive demodulators . the sign function here refers to system switching state of switch S (fig.1) this is 0 or 1 for off or on states .

IV. PV output power and phase shift of power Ripple

PV output power is variable function of output voltage (v) , current (I) and load impedance (z_L) . in this paper we are very likely to express all variables as a function of load impedance . as it was shown in fig.2 , PV output voltage is a function of load impedance , so PV array is modeled as a nonlinear voltage source , v=f(z) . in the case of long distance connection between PV arrays and boost convertor , the stray capacitance of PV arrays can't be neglected or be modeled into convertor capacitance , C . to solve this problem we model an extra capacitor , C_S , between PV arrays and boost convertor . in fig.6 , C_S is shown by dashed lines .

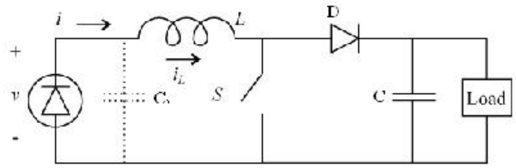

Fig.6: modeling stray capacitance of PV arrays in a practical form.

The measurable available power for RCC is obtained from equation (6) . this power out of PV arrays to boost convertor is considered to be linearized .

$$p = \frac{f^2(z)}{z_L} \qquad (6)$$

As mentioned in (2) , the optimal operating point to receive maximum available power from PV arrays is when the derivative of power , p to load impedance ,z_L equals zero . this leads us to a newer equation of RCC law to find the optimal operating point of steady state (7) .

$$\frac{dp}{dz}\Big|_{z=Z_L} = 0 = \frac{2I_0 f(Z_L)Z_L - f^2(Z_L)}{Z_L^2} \qquad (7)$$

For Z_L , where $I_0 = -(df/dz)|_{z=ZL}$

By linearizing equation (6) and converting to laplace variables and making appropriate substitutions , equation (8) is obtained according to which phase shift of power ripple versus impedance ripple is obtained .

$$\frac{\tilde{p}}{\tilde{z}_L} = \frac{2I_0 f(Z_L)Z_L - f^2(Z_L) + s\tau_0 f(Z_L)}{Z_L^2(1+s\tau_0)} \qquad (8)$$

Where $\tau_0 = Z_L C$.

As the switching frequency of boost convertor decreases or **s** goes to zero (when perturbation frequency approaches DC) :

$$\frac{\tilde{p}}{\tilde{z}_L}\Big|_{s \to 0} = \frac{2I_0 f(Z_L)Z_L - f^2(Z_L)}{Z_L^2} \qquad (9)$$

At higher switching frequency (**s** goes to :):

$$\frac{\tilde{p}}{\tilde{z}_L}\Big|_{s \to \infty} = \frac{f(Z_L)}{Z_L^2} \qquad (10)$$

The phase shift of power Ripple of a typical PV arrays with boost convertor is shown in fig.7 . the switching frequency of boost convertor is varied from 10 to 10^5 Hz .

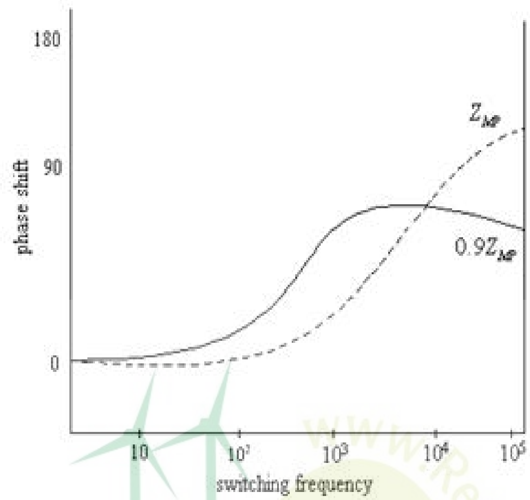

Fig.7:phase shift of power Ripple with respect to switching frequency for different operating points.

V. Case study

in this section , a real PV system consisting of a PV array , a boost convertor and a battery load is presented . the goal is to find the behavior of PV average output power versus average load impedance and voltage with respect to change of duty ratio of switch S . at a given temperature an irradiance , arrays open circuit voltage measured from it's terminals equals 12^v . design specification and circuit parameters are shown in table 2 .

item	value
PV array rating , P(watt)	15
Boost inductor , L(mh)	1
Boost capacitor , C(µf)	4700
Switching frequency , f_s(khz)	25
Output voltage	12

Table 1:design specifications and circuit parameters of presented PV system .

once the switch duty ratio (D) is adjusted on 5 percent and required variables are measured . these variables consist of average output power (P) , average load impedance (Z_L) and average load voltage (V_L) . then duty ratio is varied from 5 to 90 percent and variables are measured respectively . to see the results , refer to table 2 .

D(percent)	$\overline{P}$(watt)	$\overline{Z}_L$(ohm)	$\overline{V}_L$(volt)
5	5.8	19.5	10.5
10	6.3	17.3	10.84

15	6.92	15.39	11.33
20	7.56	13.38	11.84
25	8.3	11.9	12.4
30	9	10.34	12.96
35	9.86	8.9	13.4
40	10.76	7.59	14.15
45	11.67	6.35	14.7
50	12.6	5.28	15.3
55	13.45	4.26	15.79
60	14.07	3.38	16.1
65	14.4	2.61	16.3
70	14.17	1.94	16
75	13.2	1.3	15.34
80	11.28	0.92	13.93
85	8.45	0.56	11.68
90	5.62	0.32	8.51

Table 2 : changes of power , impedance and voltage with respect to duty ratio of presented PV system .

To better understand changes of variables , this results are shown in fig.8 and fig.9 . fig.8 shows a comparative view of changes of load impedance and output power versus duty ratio (D) .

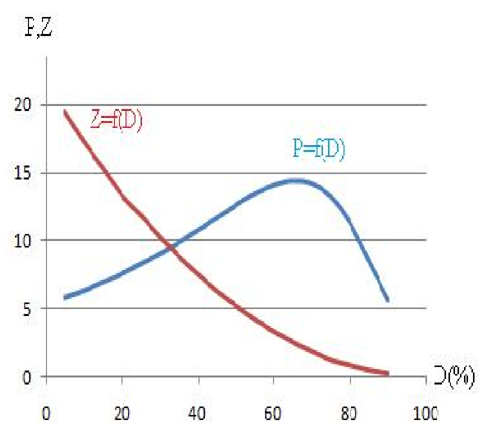

Fig.8: the average power and impedance versus duty ratio of presented PV system.

In fig.8 , P=f(D) shows changes of array output power against switch duty ratio . as is evident , the optimal operating point of duty ratio to receive maximum available power from array is around 65 percent . function Z=f(D) is changes of load impedance versus duty ratio and shows an inverse relationship between average load impedance and duty ratio .

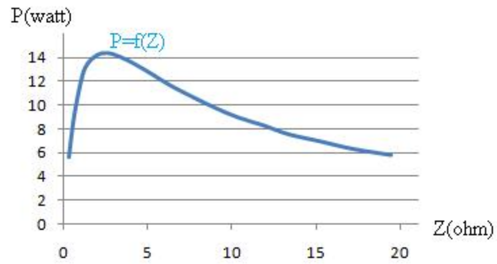

Fig.9: the average power versus average load impedance of presented PV system.

In fig.9 , P=f(Z) represents changes of average output power versus average load impedance while duty ratio is varied from 5 to 90 percent . at the maximum power point , average load impedance , Z_{MP} =2.5^{W} . the RCC parameters are also computed and are shown in table 3 .

D(%)	$\frac{dp}{dt}.\frac{dz_L}{dt}(\times 10^8)$	$\bar{z}_L$	Status
5	-21.2	19.5	>Z_{MP}
10	-34.2	17.3	>Z_{MP}
15	-41.8	15.41	>Z_{MP}
20	-44.6	13.6	>Z_{MP}
25	-43.4	11.9	>Z_{MP}
30	-39.7	10.34	>Z_{MP}
35	-34.1	8.9	>Z_{MP}
40	-27.1	7.59	>Z_{MP}
45	-20.4	6.35	>Z_{MP}
50	-14.4	5.28	>Z_{MP}
55	-0.83	4.26	>Z_{MP}
60	-0.38	3.38	>Z_{MP}
65	-0.042	2.61	>Z_{MP}
70	1.7	1.94	<Z_{MP}
75	2.12	1.3	<Z_{MP}
80	1.92	0.92	<Z_{MP}
85	1.18	0.56	<Z_{MP}
90	0.47	0.32	<Z_{MP}

Table 3: the RCC parameters of presented PV system

VI. Effect of irradiance

As previously mentioned , light irradiation disparately affects on PV output power and voltage . if we use the equivalent circuit of PV cells shown in fig.10 , the radiation dependent characteristic of a PV cells can be represented as:

$$V = n_s(\frac{AkT}{q})\ln[\frac{n_pI_{sc} - V/Z_L + n_pI_D}{n_pI_D}] - \frac{n_s}{n_p}IR_s \quad (11)$$

Where

I_{sc} : short circuit current per cells

I_D : Diode saturation current(A)

q : electron charge ($1.6e^{-19}$ C)

k : boltzmann constant($1.38e^{-23}$ J/K)

T : pn junction temperature (°K)

R_s : series resistance

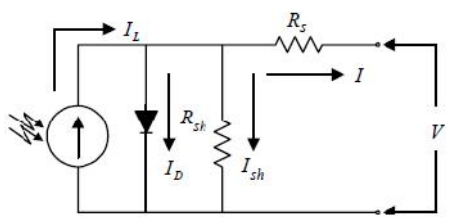

Fig.10 : equivalent circuit of PV arrays

For our typical PV array presented in case study (n_s=3 and n_p=5) and neglecting series resistant , we have :

$$V = 4\ln\left[\frac{5i_{sc} - (V/Z_L) + 0.291}{0.291}\right] \qquad (12)$$

The radiation dependent P-Z_L characteristics of presented PV system is shown in fig.11 . as is evident , the higher the radiation , the higher the output power . this study has been provided on 4 different radiation states .

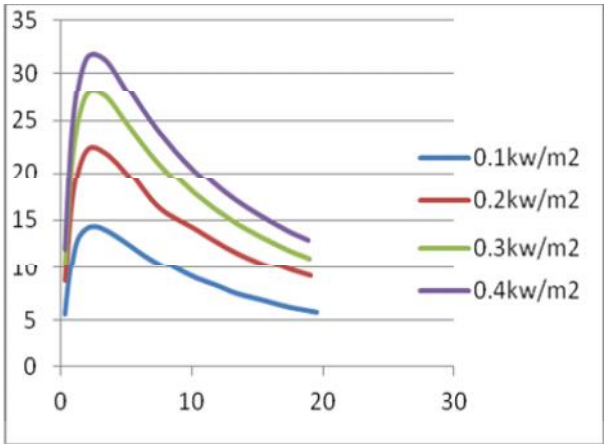

Fig.11 :the radiation dependent P-Z_L characteristics of presented PV system.

VII. Conclusion

A new method of MPPT based on impedance adaption is presented . the fundamental principle is to provide a good adaption between load impedance and PV arrays internal impedance . Ripple correlation control (RCC) is used as a basic law to correlate load impedance and find out whether z_L is below or above Z_{MP} . a boost convertor is utilized between load and PV arrays to adapt load impedance and arrays internal impedance via changing the duty ratio of switching device to maximize PV average power .

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