Modular Power Supply System With a Parallel-Connected DC-DC Conveters Using Digital Control Algorithm

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***Abstract*— An improved maximum power tracking (MPT) approach with dither signal injection is presented, including the results of computer simulation and prototype testing. It incorporates a "shared-bus" current-sharing method that can regulate many paralleled current-mode *dc-dc* converters. The approach yields nearly uniform current-sharing as well asreliable MPT performance. Utilizing the combined current sharing and MPT approaches, the MPT power system provides several advantages: ease of system powere xpansion, stable current-sharing, and autonomous MPT during loss of output voltage regulation. The robust MPT control maintains both stable amplitude and frequency of solar-array voltage ripple. The current sharing and MPPT performance of the proposed system is validated and evaluated by using MATLAB / SIMULINK software on a four-channel energy supply system.**

***Keywords*— modular structure, maximum power point tracking, MPPT, power processing, digital controller.**

I. INTRODUCTION

Solar power is popular in space applications. This industry has extreme reliability standards because of the high cost of launching space crafts, and the difficulty –impossibility in some cases- of providing maintenance and repair operations. Extra care is generally taken to provide system architectures and operating techniques that maximize the reliability of such systems. Most of control algorithms for tracking maximum power point of solar power supply systems are not able to get maximum power, The new method uses a modular structure. The utilization of the concept of modular systems using MPPT technique can also significantly improve system reliability[1].

If the control characteristics added to such systems it can distribute voltage and power through a output bus that created from current sharing algorithm. current sharing algorithm adjustment with MPPT obtain power distribution characteristics while maintaining output voltage regulation.

the Perturb and Observe (P&O) is one of the maximum power point tracking algorithems that used to tracking maximum power point in power supply systems. in this paper this algorithm is used to tracking maximum power point.

The advantage of digital controller made implementation of algorithm easy; as a result many variations of the P&O algorithm were proposed to claim improvements. in this paper his controller used to improvement performance algorithm that described in Simulated structures[2].

II. Problem Statement

Power conversion from solar-array sources [1-7] requires amore robust power system design than that for power systems with stiff voltage sources due to risks of an array voltage collapse under peak load demand or severe changes in the array characteristics. In satellite power systems, examples could be load demand above the array peak power, low solar flux, incomplete solar-array deployment, and an array pointing angle that is unexpectedly off the sun direction. Array voltage regulation is a robust method of preventing the voltage collapse since it regulates the array voltage to the voltage set point when the load demand exceeds the array peak power. To achieve near-optimum end-of-life (EOL) performance, the array voltage set point remains fixed near or at the array voltage corresponding to the array peak power at EOL. During periods of reduced solar flux or severe degradation of the array characteristics, the clamped array voltage enables reliable power transfer to the load with out requiring unnecessary power drain from standby batteries to fulfill the load demand. In this case, it is best to apply an MPT approach to continuously clamp the array voltage at a level corresponding to the array peak power .The MPT control usually operates in an oscillatory mode in which the array voltage contains an *ac* ripple component ,while continually tracking the array peak power that varies with changes in environmental conditions. Some existing MPT control approaches rarely achieve stability in both amplitude and frequency of the oscillatory array voltage ripple. These MPT approaches can lose their peak-power tracking ability and lock up in a "trapped" state far from the array peak power point. This is due to inadequacies of the feedback signals used for determining the proper control direction towards the maximum power point. Presented here in is an improved MPT control approach, using dither signal injection and array voltage regulation that optimally transfers the array peak power to the load under severe conditions. The concept is validated through computer simulation and testing of a four-channel energy supply system prototype[2].

III.Fundamentals of the Array Voltage Regulation Control System with Maximum Power Tracking

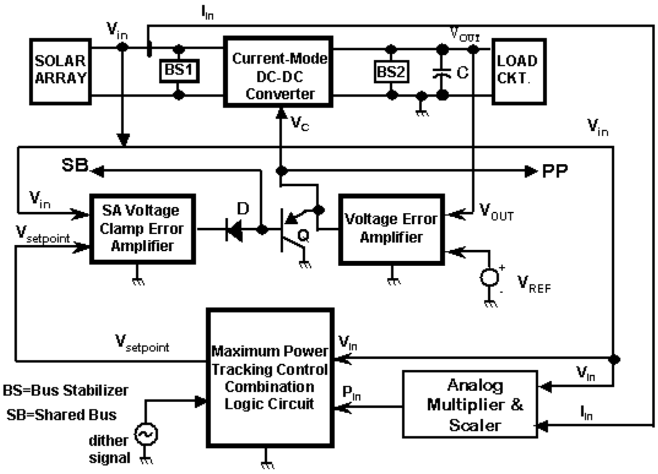

Fig. 1 MPT current-mode converter power system under array voltage regulation control mode.

Fig. 1 shows a basic power system with the solar-array voltage regulation and MPT control. The system consists of a solar-array source, current-mode converter power stage with a built-in line-filter, load, input bus stabilizer, output bus stabilizer, output voltage regulation control circuit, array voltage regulation control circuit, and an MPT control circuit. The current-mode converter power stage [8-10] is generally a conventional PWM (Pulse-Width Modulation)controlled dc-dc converter. It can be a buck (step-down),buck-boost (step-down or step-up), or boost circuit (step up)topology. The line-filter provides a means of smoothing the input current drawn from the solar array. This maintains the array current close to its steady dc value, with such a small switching ripple that the solar array operating point is considered to be stationary or nearly in a quiescent steady state. During typical operating conditions, the power system is in output voltage regulation mode. This occurs when the solar-array voltage is above the clamping set point corresponding to $V_{setpoint}$. Parallel-connected dc dc converters are usually operated in output voltage regulation (OVR) mode when system load demand is less than the array peak power. On the array *I-V* characteristic curve, the OVR mode usually yields the array operating voltage above the array peak-power voltage where the array source behaves similar to a voltage source of low internal impedance. As the load increases, the solar array operating voltage decreases until it reaches the maximum power point while the system output voltage remains regulated. Without MPT control [1-4], when the load current is above the level corresponding to the array maximum power, the array voltage decreases below the array peak-power voltage, and the system output voltage loses regulation. Without proper control, the array voltage can collapse toward zero when load demand is above the maximum power available from the array, particularly when supplying a constant-power type of load .Properly applied, MPT control can prevent the collapse of the array voltage when the power system experiences excessive load demand. One proper approach is to operate the system in a solar array voltage regulation mode in which the array voltage is clamped to a commanding setpoint, $V_{setpoint}$, which is dynamically updated by the MPT control circuit. The control processes two feedback signals, the rate of change in the array power and the rate of change in the array voltage. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. The bus stabilizer across the array voltage is properly designed [9] to achieve a small array voltage ripple and reliable stability during steady state, step-line, or step-load conditions .A dominant feature of the MPT approach, employing a dither signal superimposed on the updated set point, is the controllability of the amplitude and frequency of the array voltage ripple with respect to the amplitude and frequency of the dither signal. Using the dither signal to properly perturb the MPT control loop, the power system can operate without a trapped state in which the array voltage is settled far above or below the peak power voltage. In contrast, several MPT approaches, without dither signal injection, experience two major difficulties. One is a trapped state in which the array voltage is stabilized far from the peak-power voltage. The other is that the operating amplitude and frequency of the array voltage ripple around the peak power point are not fixed an difficult to analyze because of load dependency .Consequently, multiple MPT controllers can be employed to process power flowing from independently distributed solar-array sources. These controllers can be synchronized by sharing the same dither signal, enabling the *ac* voltage ripples superimposed on the distributed array voltages to have the same amplitude and frequency when ever respective sets of paralleled dc-dc converters are controlled in tandem to operate in the MPT mode. Referring to Fig. 1, the frequency of the dither signal is selected to be significantly below the resonant frequency,$1/LC$, formed by the net capacitance, C, across the solar array and the inductance, L, within the line-filter of the current-mode dc-dc converter. The power input port of the paralleled dc-dc converter modules requires a bus stabilizer(BS1) terminated across the solar-array source but located as close to the system input as possible to damp out *ac* energy, thus ensuring system stability during MPT[4-5].

MPPT is a control technique that leads the system to operate its solar sources at the point where they provide maximum power. This point constantly moves following changes in ambient operating conditions. A digital controller is setup to locate it in real time while optimizing other operating parameters. This control scheme can increase the energy yield of the system by up to 45%, and thus significantly reduces the size and weight of the designed system. It is also possible to interface these loads to the solar source via power electronics converters. These converters become control agents that enable a controller to choose the operating point of the solar array. If enough intelligence is added to this controller, it can locate the MPP, and force the solar array to operate at it. This process is called Maximum Power Point Tracking (MPPT). MPPT techniques ensure that the power delivered to the load is at the maximum available from the solar arrays. Hence, the control prevents the complete drop out of the system output voltage. Under normal sun insolation and healthy array source conditions, the control will not interfere with the regulation of the system output voltage because the load demand is below the maximum available power of the array source. The expansion capability of the system with such a control provides long-term cost/schedule benefits to the electric propulsion and spacecraft power systems of the next generations. In many cases, Commercial Off-the-Shelf (COTS) power converter scan be employed with such control circuitry to meet space needs In proposed system in this article, multiple solar arrays are connected to individual peak power tracker units, which composed of paralleled COTS DC/DC converters. Each of the solar arrays is individually peak power tracked with an improved MPPT algorithm. The outputs of each of the individual tracker units are connected in parallel. In such a power system, new solar arrays may be added to the system in a modular fashion simply by adding additional tracker units and adjusting a control routine to account for the additional units[6-9].

IV . P&O ALGORITHM

The PnO algorithm is a widely used algorithm Its wide application is due to the following reasons:

1. Relative theoretical simplicity
2. Ease of implementation.
3. No requirement of prior study of source characteristics.
4. General applicability for a wide range of different applications.

This algorithm determines the relative position of the maximum power point by considering the values: $V_{Hmin}\, and V_{Hmax}$

If the power increases with increasing voltage, the algorithm further increases the voltage reference with a constant voltage step $V_{Hmin}\, and V_{Hmax}$. If the power decreases with increasing voltage, the reference voltage is decreased by the same value. $\Delta V\ , \Delta P , V_{STEP}$

This method requires successive measurements of array current and voltage. The power drawn from the array is then calculated from these values. The changes in power and voltage are then calculated from two consecutive measurement cycles

Figure 2 shows a PV module's output power curve as a function of voltage (*P-V* curve), at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP. In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, _P, is observed. If the _P is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the _P is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP[10].

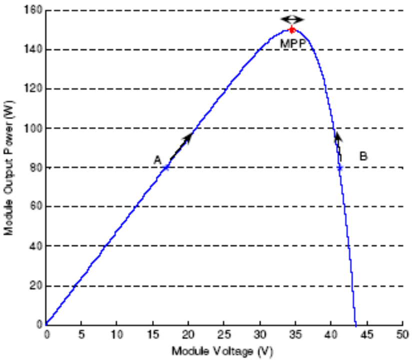

Figure 2 Plot of power vs. voltage for BP SX 150S PV module (1KW/m2, 25oC)

V. CONTROL RANGE REQUIREMENTS

The open circuit voltage of each channel is set to a nominal value of 28V with no output voltage trimming. There is certain tolerance to this value. That means that all channels' open circuit voltage values would fall between two values, V_{Lmin} and V_{Lmax} .

The OVR modifier circuit is designed to trim the output voltage up. At the maximum DAC voltage applied to it, it would add some increment Δ to the open circuit voltage, raising itto another value ranging between two values, V_{Hmax} and V_{Hmin} . Assuming small tolerance in the OVR modifier board components, it follows that

$$V_{Hmin} - V_{Lmin} = V_{Hmax} - V_{Lmax} = \Delta \qquad (1)$$

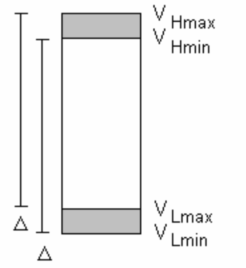

Figure 3. Trimmed and untrimmed output voltage values

The designed value for Δ should be determined to allow current sharing at all loading conditions and with worst conditions assumed in terms of output voltage reference tolerances and output resistance variations.

VoHmin and VoLmax

Assume a number of channels have already achieved successful current sharing. There is a limited range over which the output voltage at the bus V_o , can be swept. The worst case scenario is such that this control range is narrowest. It is then important to find $V_{oL\max}$ and $V_{oH\min}$. V_{oL} is the output bus voltage given that all channels are attempting to decrease their voltages while preserving current sharing. In the worst case, at least one channel has $V_{L\max}$ as its V_L value, and the lowest possible output resistance. Since proper current sharing is assumed, it processes its share of the output current, I_{sh}. It follows that:

$$V_{oL\max} = V_{L\max} - R_{o\min} I_{sh} \qquad (2)$$

Similarly, V_{OH} is the output bus voltage given that all channels are attempting to increase their voltages while preserving current sharing. In the worst case, at least one channel has $V_{H\min}$ as its V_H value, and the highest possible output resistance. Since proper current sharing is assumed, it again processes its share of the output current, I_{sh}. It follows that:

$$V_{oH\min} = V_{H\min} - R_{o\max} I_{sh} \qquad (3)$$

<u>VHmin, VLmax, and Δ</u>

With another channel added, two worst case scenarios can be assumed:

1. Added channel has $R_o = R_{omin}$, and $V_L = V_{Lmax}$, to achieve sharing:

$$V_{Lmax} - V_{oHmin} = R_{omin} I_{sh} \qquad (4)$$

substituting for $V_{oH\min}$ from (3):

$$V_{Lmax} - V_{Hmin} = \left(R_{omin} - R_{omax}\right) I_{sh} \qquad (5)$$

or

$$V_{Hmin} - V_{Lmax} = \left(R_{omax} - R_{omin}\right) I_{sh} \qquad (6)$$

2. Added channel has $R_o = R_{omax}$, and $V_H = V_{Hmin}$, to achieve sharing:

$$V_{Hmin} - V_{oLmax} = R_{omax} I_{sh} \qquad (7)$$

substituting for $V_{oL\max}$ from (2):

$$V_{Hmin} - V_{Lmax} = \left(R_{omax} - R_{omin}\right) I_{sh} \qquad (8)$$

Both worst case conditions yield the same design requirements, given in (6). Δ is the immediate design parameter, governing the design of the OVR_MOD board, it can be expressed as:

$$\Delta = V_{Hmin} - V_{Lmin} = \left(V_{Hmin} - V_{Lmax}\right) + \left(V_{Lmax} - V_{Lmin}\right) \qquad (9)$$

The second term directly relates to the COTS converters voltage reference tolerance and can be determined from their datasheet[11-12].

$$\Delta = V_{H\min} - V_{L\min} = \left(V_{H\min} - V_{L\max}\right) + \left(V_{L\max} - V_{L\min}\right)$$

VI. Paralleled Converter System with MPT

Shown in Fig. 4 is the basic architecture of the MPT solar array power system [11] that autonomously adjusts its operating condition to be near or at the maximum power point of the solar-array source, *SA,* or regulates the system output voltage, *Vo*, when the net load demand is below the peak power. At the same time, near-uniform current sharing [8, 10] among dc-dc converter modules connected in parallel is achieved through the use of a shared-bus (SB) and parallel control pins (PP). One shared-bus (SB) is used in this power system architecture, providing system control for uniform current-sharing while also satisfactorily meeting the control purpose – maximum power tracking when experiencing over-demanding load, or system output voltage regulation when the net load demand is below the available source peak power. Each converter module may have its SB and PP unconnected (floating) when used as a stand-alone unit, thus regulating its own output voltage. Otherwise, the SB or the PP of each converter module is used as a commanding voltage input for regulating the converter power stage as a voltage-controlled current source. When the parallel pins and shared-buses of many identical converter modules are respectively tied to gether to form two unified control ports, all converter modules are regulated by the same controlling voltage generated from either the MPT controller or the OVR circuits residing within the paralleled converters. This results in not only nearly a uniform distribution of the converter output currents but also the elimination of undesirable interactions experienced by other approaches of current-sharing during output voltage regulation mode. The implemented configuration shown in Fig. 4 is a parallel-connected dc-dc converter system interfacing between a solar-array source and a common system load .In this configuration, only one MPT controller is needed for tracking the peak-power point of the solar array source. The MPT controller has a controlling output port commonly connected to the

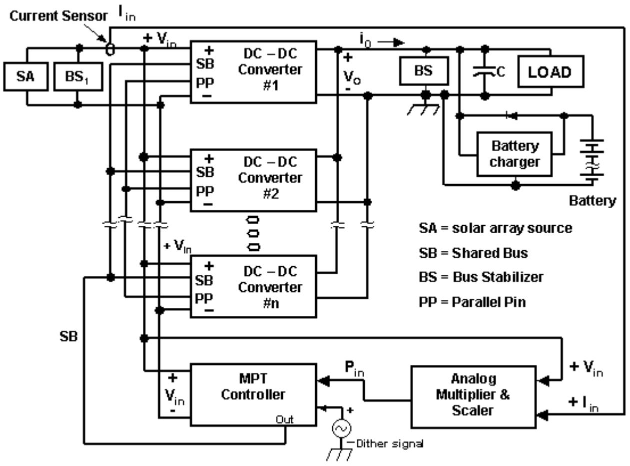

Fig. 4 Basic Configuration of Paralleled Converters with MPT Controller and Single Shared-Bus

paralleled SB provided by the parallel-connected dc-dc converters. Therefore, physicallay out and inter-connection of the system should be carefully implemented to minimize chances of a single point failure on the paralleled shared bus or parallel-pins. As an option shown in Fig. 2, the battery charging circuitry as well as the standby battery set-up can be connected across the system output bus, *Vo*, to either replenish the battery charge or supplement the load demand[7-10].

VII. simulation & Implementation proposed system

As mentioned earlier the Perturb and Observe (PnO) is one of the maximum power point tracking algorithems that used to tracking maximum power point in power supply systems. in this paper this algorithm is also used to tracking maximum power point but the P&O algorithm will oscillate around the optimal operating voltage when the maximum power operating point is reached. This result in a waste in PV power delivery. To solve this problem to escape the local maximum points, a dither signal (sinusoidal perturbation signal) can be added to the reference control voltage of the array. This signal if of enough amplitude can drive the systems into the region leading to the absolute maximum of the P-V curve. In this section, the proposed four-channel system with parallel structure are presented. This model presented in the following figure, which is shown partially is investigated. A model of the system was built in Matlab's Simulink in order to simulate the current sharing algorithm. This model is detailed, and can account for a number of non-idealities in the system. The experimental results later collected closely match the results this simulation platform yields.

The basic simulation setup is shown here. The simulation platform consists of four solar powered channels. Each channel takes the open circuit voltage and short circuit current values as inputs. It produces a value representing the output current it delivers. All the output currents are summed up and fed to a constant current (CC) load simulator, with finite capacitance. The load simulator uses the current values to calculate the output voltage, this is fed back to the solar channels in order for them to determine the output currents, and to run in output voltage regulation mode when required to. In order to realize current sharing, the current sharing bus is constructed.

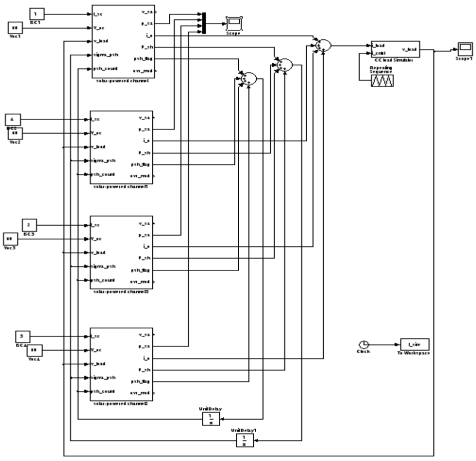

Figure 5. Overall system simulation model

To simulate the transmission enabling/disabling feature of the applied scheme, two signals are generated per channel; these are the p_share value, and the psh_flag. Each signal type is collected from all four channels and summed. The two resultant values are then fed back to all channels. Each solar powered channel contain three main blocks, these are the solar array simulator (SAS), the power stage, and the digital control algorithm. The solar array simulator model produce a value for the solar array voltage based on the current drawn from the array and the curve parameters, namely, open-circuit voltage, and short-circuit current The power stage takes the voltage and current values from the SAS, and uses them to determine the output current, and to update the input current value. The power stage model basically uses the power conservation concept to determine the output current based on the input power, and the output voltage values. The output voltage value is generated by the load simulator. the digital controller receives scaled solar array voltage and current measurements from the analog conditioning circuits. It senses these measurements through an analog-to-digital converter (ADC) and processes them to locate the MPP. This controller then provides a voltage reference through a digital-to-analog converter (DAC) that corresponds to the MPP. The input voltage regulation mode is then responsible for matching the operating point of the solar array to it.

The simulation results for the four channel model shown and described above are shown here.

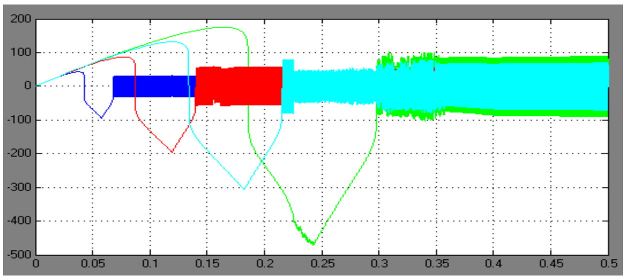

Figure 6. Waveform output power channels

Upper figure shows simulation results. At low power levels (initial time), all forms of waves follow each other with the same output waveform, but if the total power (power load) is high, all channels at different times switches to the maximum power point tracking mode and their power values obtained from maximum power from solar arrays according to them. the maximum power value during 0.23 to 0.30 seconds is clear. at the same time other channels operate in output voltage regulation.

In the proposed system, The open circuit voltage of each channel is set to a nominal value of 28V with no output voltage trimming. Maximum power output from this system is about 490 watt.

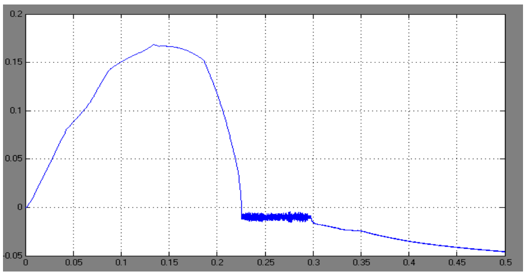

Figure 7. Output load voltage waveform at Output voltage

The upper figure represents shown the output voltage ripple during 0.23 to 0.30 seconds. In this region system operates in MPPT mode.

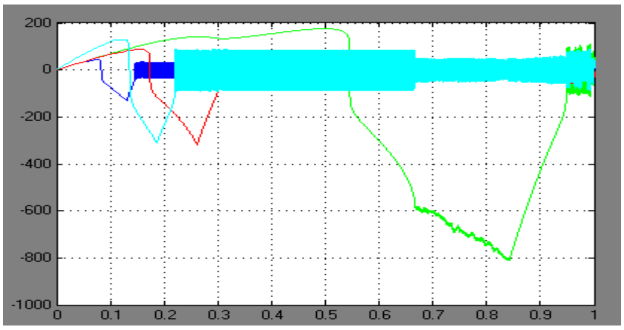

Figure 8. Waveform output power channels under heavy load condition

. The upper figure of the simulation results represents the amount of input power being processed for each of the four channels in the system under heavy loading condition. Current sharing algorithm decrease the output Reference voltage channels to achieve the maximum power point from them. output Reference voltage for number of First to third channels is 15 volts and for fourth channel is 28 volts. The following figure shows the output power channels. Output power channels is About 800 watts that in comparison with the first mode is greater than 300 W.

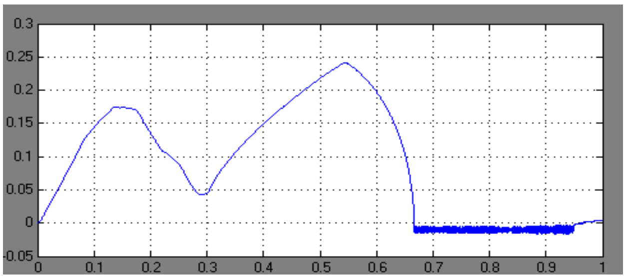

Figure 9. Output load voltage waveform at Output voltage under heavy load condition

In upper figure, the maximum power value during 0.67 to 0.95 seconds is clear. at the same time other channels operate in output voltage regulation. This long time system MPPT operation, that is 0.33 seconds shows that the load is heavy and system is trying to extract maximum power from its corresponding arrays during this time and it's the reason why the MPPT operation time is so long.

In addition, compared with the first case each channel extracted more output power from solar arrays according with their, that Indicating a heavy load on the system.

The bellow figure of the simulation results represents the amount of input power being processed for each of the four channels in the system under light loading condition. Current sharing algorithm increase the output Reference voltage channels to achieve the maximum power point from them. Output Reference voltage for number of First to third channels is 50 volts and for fourth channel is 28 volts.

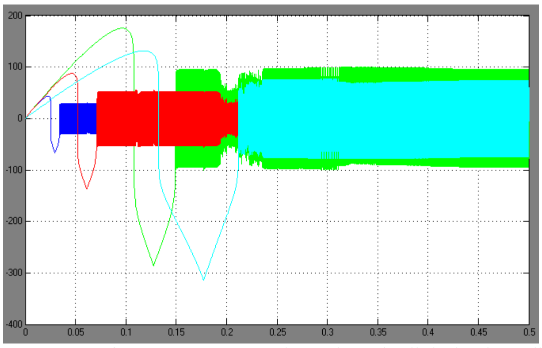

Figure 10. Waveform output power channels under light load condition

The following figure shows the output power channels. Output power channels is About 280 watts that in comparison with the first mode is smaller than 210 W.

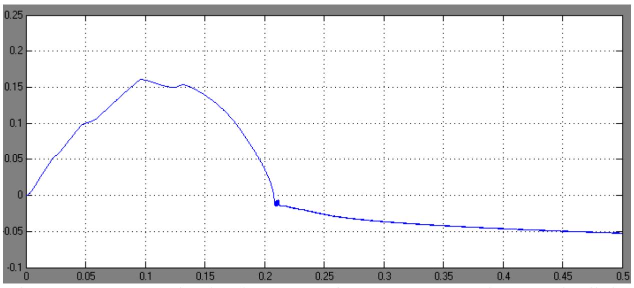

Figure 11.. Output load voltage waveform at Output voltage under light load condition

In upper figure, the maximum power value during 0.213 to 0.219 seconds is clear. at the same time other channels operate in output voltage regulation. This short time system MPPT operation, that is 0.006 seconds shows that the load is light and system is trying to extract maximum power from its corresponding arrays during this time and it's the reason why the MPPT operation time is so short.

VII. Conclusion

An expandable power system with robust multiple power point tracking capabilities is presented in this paper. The system incorporates a controller to track multiple peak power points of a plurality of solar arrays. Paralleled current mode DC/DC converters, coupled between a solar array and the load acts as a peak power track module for each solar array.

The performance of the proposed system is validated and evaluated by using MATLAB / SIMULINK software on a four-channel energy supply system.

References

[1] H.Koizumi and Kurokawa“A novel maximum power poin tracking method for PV module integrated converter,” in *Proc.IEEE power Electron.spec.Conf.*,2005,pp.2081-2086.

[2] J. H. R. Enslin., M. S. Wolf., D. B. Snyman., and W.Swiegers.,“Integrated photovoltaic maximum power point tracking converter.,”*IEEE Trans.Ind.Electron*. .,vol.44.,pp.769-773.,Dec.1997.

[3] N. Femia., G.Petrone., G. Spagnuolon., and M. Vitelli., “Optimization of Perturb and observe maximum power point tracking method., ”*IEEE Trans.Power Electron*. ,vol.20.,no.4.,pp.963-973., Jul.2005.

[4] Noguchi.,T.,Togashi.,S..,Nakamoto.,R.,“Short-current pulse-based maximum-power-point tracking method for multiple photovoltaic-and-converter module system., ”*Industrial Electronics. ,IEEE Transactions on*.,Vol.49.,No. 1.,pp.217-223.,Feb.2002

[5] Noguchi.,T.,Togashi.,S..,Nakamoto.,R. ,“Short-current pulse based adaptive maximum-power-point-tracking for photovoltaic power generation system,”*Industrial Electronics*,2000.*ISIE 2000.Proceeding of the 2000 IEEE International Symposium on*,Vol. 1,pp.157-162,Dec.2000.

[6] Perreault , D.J. Sato,K.Kassakian, J.G. ,“ Switchin-ripple-based current sharing for paralleled power converters,” *Power Conversion Conference – Nagaoka* 1997. ,*Proceedings of the*,Vol. 1 ,pp.473-478, Aug.1997.

[7] R.Dougal,L.Gao,S .Liu, and A.Iotova,“Apparatus and method for enhanced solar power generation and maximum power point tracking,”Patent PCT Number WO 2007/124059 A2,Nov.2007.

[8] R.Gules, J.DePellegrin Pacheco,H.L.Hey , and J. Imhoff,“A maximum power point tracking system with parallel connection for PV stand-alone applications,”*IEEE Trans.Ind.Electron*. ,vol.55,no.7,pp.2674.2683,Jul.2008.

[9] Shieh,J.J,“Analysis and design of parallel-connected peak-current-mode-controlled switching DC-DC power supplies,”*Electric Power Applications,IEEE Proceedings*,Vol 151,No.4 pp.434-442,July2004.

[10] W.Xiao, W. G.Dunford ,P .R .Palmer, and A.Capel,“Application of centered differentiation and steepest descent to maximum power point tracking,” *IEEE Trans.Ind. Electron*. ,vol. 54, no. 5, pp.2539-2549,Oct.2007.

[11] W.Xiao ,N.Ozog, and W.G.Dunford,“Topology study of photovoltaic interface for maximum power point tracking,”*IEEE Trans.Ind.Electron.* ,vol.54,no.3,pp.1696-1704,Jun.2007.

[12] Y.C.Kuo,T.J.Liang,and J.F.Chen,“Novel maximum-power-point-tracking controller for photovoltaic energy convertion system,”*IEEE Trans.Ind.Electron*. ,vol.48,no.3,pp.594-601,Jul.2001