Renewable Energy Harvesting for Low Power Wireless Monitoring Networks

Zubair Rehman, Ibrahim Al-Bahadly, and Subhas Mukhopadhyay

Abstract—**Energy Harvesting Technologies for wireless electronics networks have undergone a tremendous development in the recent past. Several micro level energy generating units have been developed to convert variety of renewable energy sources to useable electrical energy. In order to integrate and exploit maximum benefits from renewable sources, an intelligent power electronics interface is mandatory. This paper presents a multiport power electronics circuitry to extract maximum energy from renewable energy sources and route it to power up wireless electronics networks. This new topology has ability to cope with different voltage level requirements and is capable of integrating several energy sources to satisfy the variable load demands. The sources can be utilized independently or concurrently. Surplus energy can also be stored and made available in case of absence of renewable energy sources. Analytical and simulation results in Continuous Conduction mode are presented and are validated by experimental results on a prototype model.**

Index Terms—**Single inductor–multi output (SIMO), pulse width modulation (PWM), and continuous conduction mode (CCM).**

I. Introduction

In today's world wireless electronic networks have become an integral part of remote monitoring systems. These sensing networks are extensively being used in bio medical systems [1]-[3], Air Quality monitoring [4], Health care systems [5]-[7] Structural Health Monitoring System, aerospace systems [8], Internet of Things and other smart applications [9]. These remote networks are playing very vital role in surveillance and monitoring as these are placed close to the area of interest and are expected to last for a longer period of time. However by doing so the sensing units loose the advantage of being powered up through conventional sources i.e. utility power and they rely heavily on batteries. But the issue of battery replacement adds on to the problems like service interruption, time and cost of operation. This limited network life due to lack of continuous power is the major bottleneck in the deployment of wireless networks in critical applications. Therefore, it is required to design wireless sensor networks which depend on self-generated power. Such a power can be generated from the ambient and renewable sources of energy like wind, solar, vibration and radio frequency. In recent years, energy harvesting has arisen as a promising technology to extend the life span of sensor networks by continuously harvesting green energy from environmental sources. Furthermore the rapid advancement in wireless technologies and power electronics devices has enabled the increased use of self-sufficient sensor network systems for several monitoring applications. The viability of powering up the wireless sensor networks through energy harvested from renewable energy sources has been demonstrated in the research [10]-[13]. Energy harvesting system comprises of three major components namely the generating unit, power electronics circuitry and the storage unit. Several sources of renewable energy and methods to harvest them are explained in [12], [14]-[16]. This work is focused on power electronics circuitry which is responsible to transmit power from source to load. Remote monitoring networks are composed of different units like communication equipment, microprocessor, radio frequency module and memory unit. Each of these components may require different voltage levels. To fulfil these different voltage levels a single inductor multiple output (SIMO) converter may be deployed in the power electronics circuitry portion of wireless sensor network as it can provide multiple output voltages with reduced components, high power density and uses a limited printed circuit board area [17]. Different SIMO converters have been presented in the research for multiple applications [18]-[23]. Methodologies describing the control of SIDO converters have also been developed to regulate outputs while keeping related issues like cross regulation to a minimum level. A digital control methodology is presented in [24]-[26]. Whereas [27] implements a multivariable control scheme and an adoptive mode control is used in [28].

In this paper a multi input-multi output dc-dc buck converter is presented. The converter assimilates multiple energy sources at input ports and provides multiple regulated outputs to power up different loads with different voltage levels of wireless sensor electronic networks. Moreover it has one bi-directional port to accommodate a storage device. The advantages of the proposed topology over the topologies in the literature cited are (i) it can accommodate numerous sources at the input these sources can be employed independently and simultaneously. (ii) It is capable of powering up multiple loads with different voltage levels. (iii) in addition to provide regulated output to the load, this converter is capable of harvesting maximum power from the input sources. (iv) Surplus energy can be stored in the battery and made available in the absence of renewable energy sources.

The paper is organized as follows. Section II describes converter's design. Analysis of the converter is done in

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Section III. Section IV relates to modelling of topology. Section V presents simulation results. Experimental results are shown in Section VI. The conclusions are drawn in Section VII.

II. Topology Description

The proposed converter is shown in Fig. 1. An arbitrary number of energy sources are connected at the input. A battery to store extra energy is connected at one of the output ports. Numerous Loads with the resistances 'Ri' (i= 1…n) are connected to the other output ports. All the outputs use only one inductor, with inductance 'L' to draw current from the sources. Input power from several sources is controlled through switches M_1 to M_m individually and simultaneously. Similarly output voltages are regulated through switches Q_1 to Q_n. Battery charging and discharging circuit is controlled by the switches M_{BC} and M_{BD} respectively.

The input voltages can power up the load separately or all at once and any source can be added and taken advantage of as and when available. Similarly the output voltages are regulated to their desired values irrespective of the state of the input voltages and loading conditions. Battery charging and discharging can be controlled subject to the status of sources and condition of loads.

III. Design of Components

The section discusses the design parameters of the proposed topology for steady state operation in continuous conduction mode

A. Inductor Rating

Determining the inductor rating is the most critical step in designing of multiport converter. Saturation in the inductor is determined by the peak current passing through it which intern is used to determine the size of the inductor. The inductor peak current can be determined by the equation

$$I_{peak} = I_{omax} + \frac{\Delta I_L}{2} \tag{1}$$

Whereas the current ripple ΔI_L can be found as

$$\Delta I_L = \frac{1}{f_{sw}L}\left(V_{in,max} - V_{out}\right)\frac{V_o}{V_{in,max}} \tag{2}$$

Here f_{sw} is the switching frequency, L is the inductance of the inductor. Writing ΔI_L in terms of current ripple ratio "f" evaluated at maximum load current, I_{omax} gives

$$ŕ = \Delta I_L / I_{omax} \tag{3}$$

Now from (2) and (3) we can get the minimum inductance value of the inductor

$$L = \frac{1}{I_{omax}\, ŕ f_{sw}}\left(V_{in,max} - V_o\right)\frac{V_o}{V_{in,max}} \tag{4}$$

In case of multiple output buck converter, the inductor is shared between the outputs therefore the value of inductor needs to be selected so that the ripple current of the largest output does not increase. So the value of inductor can be determined as

$$L = max.\left(\frac{1}{I_{omax}\, ŕ f_{sw}}\left(V_{in,max} - V_{o,j}\right)\frac{V_{o,j}}{V_{in,max}}\right) \tag{5}$$

(j = 1,2…..n)

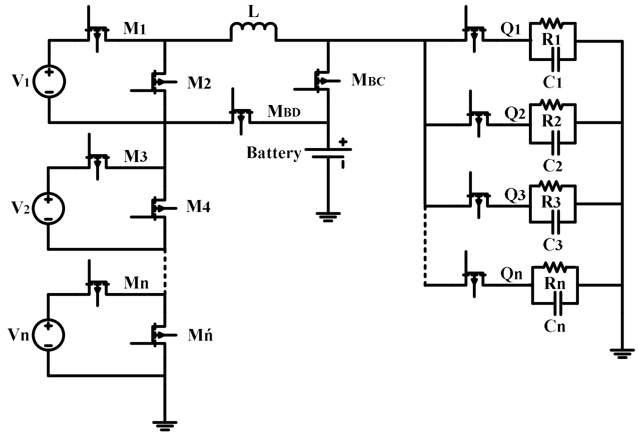

Fig. 1. Multi input-multi output converter.

B. Output Capacitor Rating

Output capacitor plays an important role in converter by reducing the output voltage overshoot and ripple. Insufficient output capacitance causes large voltage overshoots and large ripples. The designed capacitor should be large enough to prevent the inductor's stored energy to surpass the output voltage beyond the specified maximum value when the load is instantly removed. The max value of output voltage overshoot is specified at the time of design and can be calculated by the following equation.

$$V = \left[\sqrt{V_o^2 \frac{L(I_{omax}+{}^{\Delta I_L}/_2)^2}{C_o}}\right] - V_o \tag{6}$$

Rearranging (6) for the value of capacitor C_o

$$C_o = \frac{L\left(I_{omax}+ {}^{\Delta I_L}/_2\right)^2}{(\Delta V+V_o)^2 - V_o^2} \tag{7}$$

The value of the output Capacitor can be found by (7) after specifying the design value of ΔV.

IV. Steady-State Analysis

Considering the operation of converter with 'm' inputs and 'n' outputs and by applying the Volt-Second balance principle we get the voltage across the inductor

$$V_L = \sum_{i=1}^{m} V_{in,i}D_i - \sum_{j=1}^{n} V_{o,j}Q_j = 0 \tag{8}$$

Here V_L is the voltage across the inductor, V_{in} in the input or source voltage, V_o is the voltage across the output, D is the duty ratio for switch connected to input voltage and Q is the duty ratio for switch connected to output voltage.

Similarly if we apply capacitor charge balance principle we get

$$Q_j I_L - \frac{V_{o,j}}{R_j} = 0 \quad (j = 1 \ldots n) \tag{9}$$

By solving (8) and (9) we can find the values of current across the inductor and the output voltages. Thus the average current across the inductor is

$$I_L = \frac{\sum_{i=1}^{m} V_{in,i} D_i}{\sum_{j=1}^{n} R_j Q_j^2} \tag{10}$$

Similarly the voltage at the *jth* output is given by

$$V_{o,j} = \frac{Q_j \sum_{i=1}^{m} V_{in,i} D_i}{\sum_{\alpha=1}^{n} k_{\alpha,j} \sum_{j=1}^{n} Q_j^2} \tag{11}$$

Here $k_{\alpha,j}$ is the ratio of load resistances

$$k_{\alpha,j} = \frac{R_\alpha}{R_j} \tag{12}$$

The input power of the converter can be adjusted by the input duty cycles through an effective control scheme implemented by a controller. The input power is dependent on average input current. The average input current can be represented as

$$I_{in} = D I_L \tag{13}$$

Here I_{in} represents the input current from one or combination of more than one available input sources. Similarly D is the duty ratio for one or combination of more than one input voltage sources. If V_{in} is the total input voltage then input power can be determined as

$$P_{in} = V_{in} D I_L \tag{14}$$

By putting the value of I_L from (3) we get

$$P_{in} = V_{in} D \frac{\sum_{i=1}^{m} V_{in,i} D_i}{\sum_{j=1}^{n} R_j Q_j^2} \tag{15}$$

As per (15), the average input power is not only dependent on average inductor current but also is a function of input voltage, input duty ratios and output duty cycles. This suggests that the inductor current and input power can be controlled by adjusting the duty ratios.

V. Modelling of Multiport Topology

In order to demonstrate the effectiveness of the proposed circuitry to harvest energy from different intermittent sources, a three input two output model is built as shown in Fig. 2. The output voltage equations for the circuitry are depicted as (16) and (17). Simulation results of the model will be presented followed by the experimental results on laboratory scale prototype model.

$$V_{o1} = q_1 R_1 \frac{(V_1 d_1 + V_2 d_2 + V_3 d_3)}{q_1^2 R_1 + q_2^2 R_2} \tag{16}$$

$$V_{o2} = q_2 R_2 \frac{(V_1 d_1 + V_2 d_2 + V_3 d_3)}{q_1^2 R_1 + q_2^2 R_2} \tag{17}$$

Here V_{o1} is the output voltage and R_1 is the load resistance connected across output port one. V_{o2} is the voltage and R_2 is the load resistance connected at output port two d_1 , d_2 and d_3 are the duty ratios for switches M_1, M_2 and M_3 whereas q_1 and q_2 are the duty cycles for output switches Q_1 and Q_2. The switches M_2 , M_4 and M_5 are turned ON only when M_1, M_3 and $M_5$are OFF. The switchM_{BC} is turned ON when surplus energy is required to be stored in battery and the switch M_{BD} is turned ON when renewable energy sources are not available or not have enough power to satisfy the load demand and battery is required to deliver additional power.

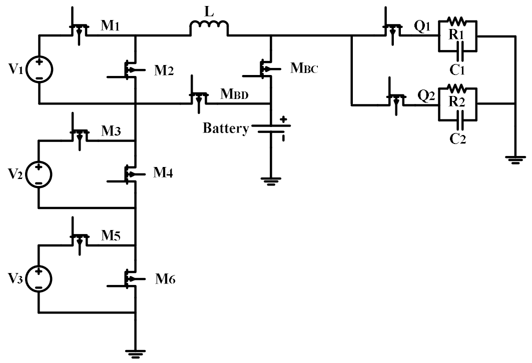

Fig. 2. Three input-two output converter model.

VI. Simulation Results

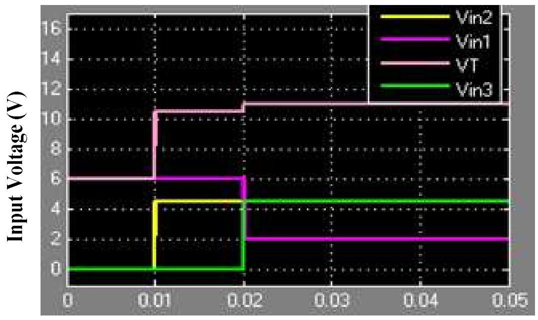

Fig. 3. Variation in input voltages of converter.

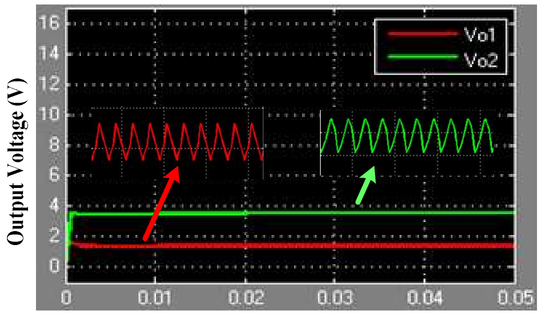

Fig. 4. Regulated output voltages of converter.

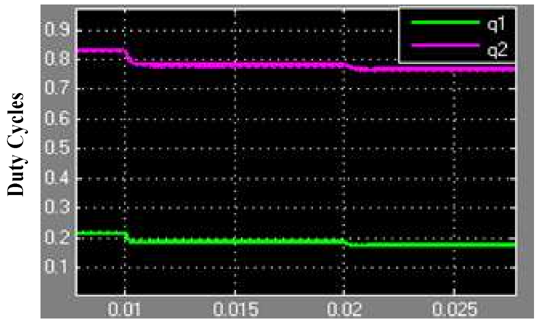

Fig. 5. Output duty ratios q_1 and q_2.

The presented circuitry is modelled and simulated in MATLAB/Simulink. Three energy sources are connected at the input each providing 6 volts at the maximum power point of respective renewable energy source. Two different loads have been connected at the output ports. Load one needs regulated 1.5 Volts supply and load two requires 3.3 volts supply. At the start of simulation, only source one is available with 6V input voltage. Both the output voltages are regulated at the desired values. At time $t = 0.01$s, source two also comes up and starts providing 4.5 Volts input voltage. So the total input voltage increases to 10.5 volts. To keep the output voltages at reference values, the output duty cycles q_1 and q_2 are reduced. At time 0.03s, source one reduces to 2 volts but at the same time source three adds another 4.5 volts to the system pushing the total input voltage to 11 volts. Duty cycles q_1 and q_2 are further reduced to keep the output voltages to a desired level. The input duty cycles d_1, d_3 and d_5 are used to extract maximum power from input sources. From these results it is evident that despite of all the variations in the input voltages, the output voltages are regulated at the desired values. Furthermore all the input sources can power up the loads individually and simultaneously. Variation in input voltages (V_{in1}, V_{in2} &V_{in3}) is shown in Fig. 3. Regulated output voltages (V_{o1} and V_{o2} are shown in Fig. 4.

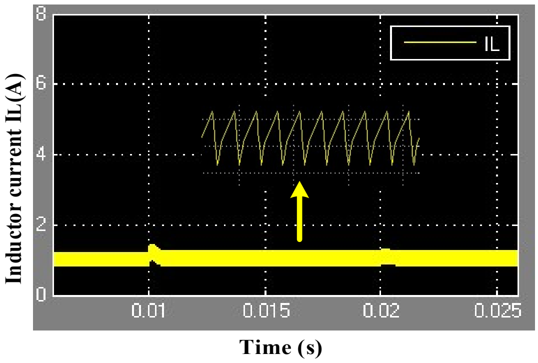

Fig. 6. Inductor current.

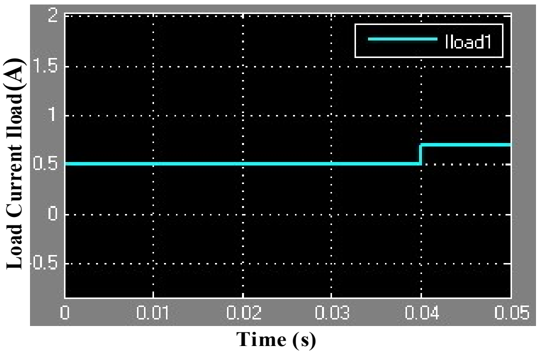

Fig. 7. Step change in output current.

Change in output duty cycles q_1 and $q_2$is depicted Fig. 5 and Inductor current is shown in Fig. 6. Simulation studies are further extended to analyze the behavior of the converter under variations in load current. The current of load one is increased from 500mA to 700mA at time 0.04s. As a result of this change the inductor current is also increased so is the increase in output duty cycle is observed. However the output voltages do not vary and remained regulated to intended values. Step change in load current is shown in Fig. 7. Whereas increase in output duty cycle q_2 and increase in inductor current due to increase in load current is shown in Fig. 8 and Fig. 9 respectively. The results demonstrate that the output voltages are tightly regulated despite of variations in input voltages and load current.

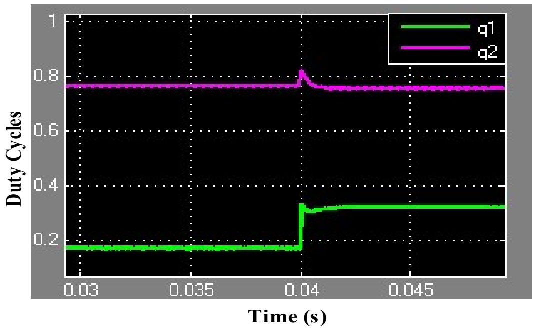

Fig. 8. Output duty ratios q_1 and q_2 during change in load current.

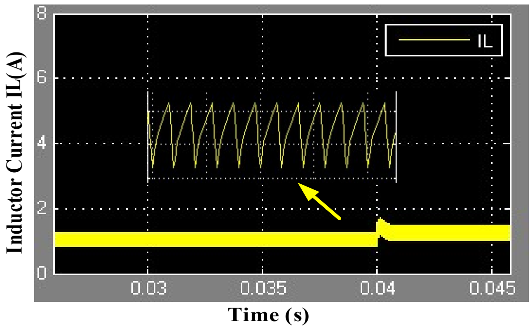

Fig. 9. Change in inductor due to change in load current.

VII. Experimental Verification

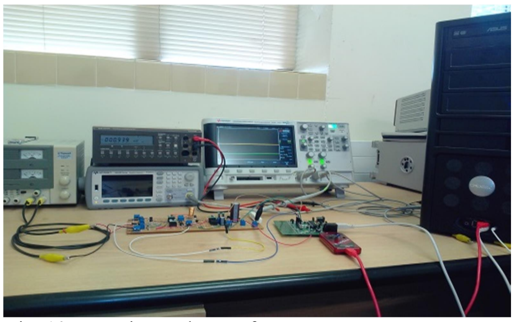

Fig. 10. Experimental setup for prototype DIDO converter.

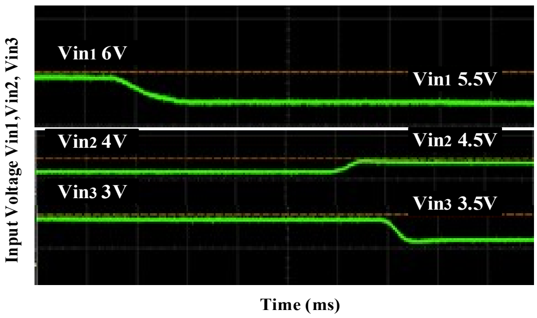

Fig. 11. Variations in input voltages of converter.

In order to verify analytical and simulation results, a low power prototype model is built. Experimental setup is shown Fig. 10. Digital Control scheme with PI control is implemented by microcontroller Microchip dsPIC 30F2020.

Input energy sources are represented by constant DC voltage sources in the laboratory setup. Duty ratios for the input voltages d_1, d_2 and d_3 are kept at 0.8. Duty cycles q_1 and q_2 regulate the output voltages to desired level i.e. 1.5 and 3.3V. At the start of the experiment, all the three sources are available at the values V_{in1} (6V), V_{in2} (3V) and V_{in3} (1.5V). The outputs are regulated at 1.5 and 3.3 volts. A change in the input voltage V_{in1} is applied and it reduces from 6 volts to 5.5 volts. No significant change in the output voltages is observed. Another variation in the input voltage in enforced by increasing the voltage source V_{in2} from 4 volts to 4.5 volts however in spite of this variation, the output voltages did not shown any major disturbance. Another variation in the input voltage occurs in the form of reduction in source voltage V_{in2} from 3 volts to 2.5 volts. Again it is observed that the output voltages remain tightly regulated. Variation in Input voltages is shown in Fig. 11. Regulated Output voltages are shown in Fig.12 and inductor current is shown in Fig. 13. Likewise to observe the behavior of the proposed topology under variations in loading condition a step change in the current load one is applied and the load current increases from 500mA to 700mA. It is observed that the output voltages remain unchanged while there is an increase in the inductor current. The situation is illustrated in Fig. 14 and Fig. 15 respectively. The experimental results also endorse simulation and analytical results.

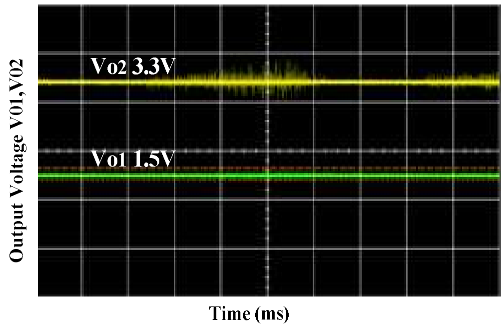

Fig. 12. Regulated output voltages of converter.

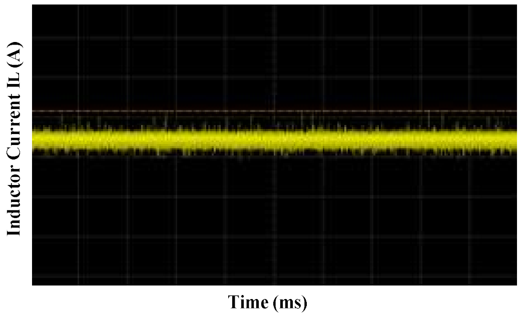

Fig. 13. Inductor current for converter.

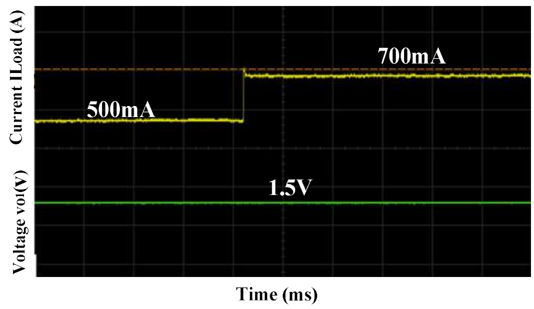

Fig. 14. Step change in load current.

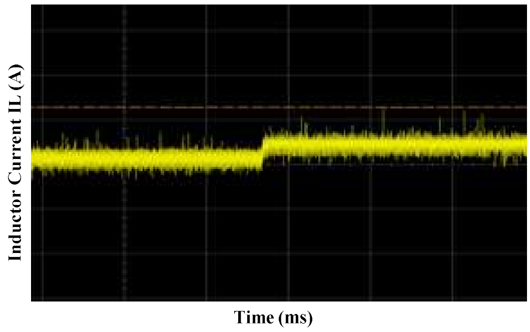

Fig. 15. Increase in Inductor current due to increase in load current.

VIII. Conclusion

A multi input multi output power electronics circuitry to harvest energy from ambient energy sources for wireless electronic networks is presented in this paper. The new topology can accommodate several energy sources at the input ports and provides regulated outputs to several loads with different load requirements. Furthermore it can also extract maximum power from renewable energy sources and can store the surplus energy in a battery for later use. Operation of the presented converter is investigated under different conditions. Simulation studies of the topology have been conducted in MATLAB/Simulink for Three input-Two output mode. The results suggest that the proposed circuitry provides an excellent response to variations in input voltages due to asymmetrical availability of power from intermittent renewable energy systems and variation in load current. Experimental results have also proved the suitability of proposed circuitry to harvest energy from renewable/ambient energy sources for a wireless sensor networks deployed in remote location.

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