A 1MHz Oak Ridge AC / DC Converter for UAV Contactless Charger Implementation

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Abstract— **In this paper, a 1 MHz single-phase Oak Ridge Converter (ORC) AC/DC wireless power transfer (WPT) system is introduced for unmanned air vehicle (UAV) charging applications. The proposed advanced solution eliminates the design, weight, volume, and the cost of the power factor correcting (PFC) front-end rectifier compared to the conventional practices. Additionally, grid power quality requirements can be achieved with the presented innovative idea. With this method, single stage WPT primary side uses the hybrid grid frequency and high frequency (60 Hz and 1 MHZ) from ac source through the coupler coils and to UAV battery with GaN FETs. Experimental results of the single-phase system is presented to confirm the mathematical analyses with the source voltage of 110 $V_{AC,RMS}$ and output voltage of 40 V_{DC} at 1 kW power with 6 inches air gap between couplers. The primary coupler consists of a ferrite-backed single-turn coil with a radius of 1.5 ft, and the secondary coupler is made with an air-core single-turn coil with radius of 1.2 ft. The system overall ac to dc efficiency is measured 77 % acquiring 0.99 power factor (PF) and 3.3 % current total harmonic distortion (THD) at 1 kW power.**

Keywords— UAV, contactless, energy, transfer, Oak Ridge, resonant, converter, ac-to-dc, 1MHz

I. INTRODUCTION

A critical challenge facing the current state-of-the art electric unmanned aerial vehicles (UAVs) is the low energy density of batteries [1]-[2]. Unfortunately, as the battery power is consumed, the drone efficiency decreases since there is no corresponding decrease in mass, as would happen in fueled propulsion [3], [4]. Their flight times are typically limited up to 5-15 minutes and to a range of a few miles. Consequently, limited flight range is a critical challenge faced by business sectors which would have significant benefits in adopting drones for delivery, logistics, and security services [5].

Wireless charging technology is conceptually very well suited for UAV chargers because it does not require any physical electrical contact and thereby not hampered by environmental factors or dependent on physical contact mechanisms [6]-[8]. A practicable wireless power transfer system tailored to extend UAV flight range is necessary to enhance the applicability of UAVs for plethora of applications [9]. There is a critical need for a convenient and practicable way of extending flight range and time without having the requirement to land for plug-in charging, and wireless power transfer-based solution is ideally suited to realize this approach [10]-[11].

In this study, an economically viable and practicable solution is developed using ORNL patented technology called Oak Ridge Converter [12] to significantly alleviate or eliminate range limitation of UAVs. The proposed WPT system for UAV applications is an economically viable and practicable in-the-field charging system that the overall objective is to eliminate range anxiety for UAVs to harness the full potential of UAV based systems. The proposed Oak Ridge Converter (ORC) topology merges 60 Hz grid frequency with 1 MHz high frequency switching signal through GaN FETs. Moving through the single-phase coupler coils with the resonant network, this hybrid frequency power is then rectified to dc without a power factor correction (PFC) rectifier in the front end. This innovative solution helps eliminate the system design complexity and cost while meeting the grid side THD and PF requirements [13], [14]. Single-phase ORC GaN FETs are operated at 50% duty cycle and opposite gate waveforms through negative and positive half cycles of source for lower and upper half-bridge legs at the constant operating frequency. The system theoretical analysis is also explained for series-series connected tuning topology. To illustrate the system operation, experimental results of the proposed converter are demonstrated with a single-phase source of 110 $V_{AC,RMS}$ and output load voltage of 40 V_{DC} at 1-kW power while achieving 77% efficiency with 3.3% current THD and 0.99 PF in the laboratory conditions.

This manuscript has been authored by Oak Ridge National Laboratory, operated by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

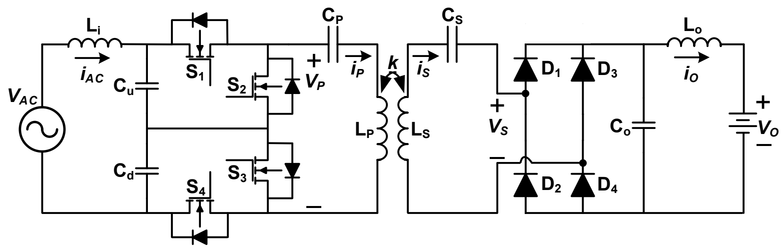


Fig. 1. The presented single Oak Ridge Converter (ORC) for UAV WPT chargers.

II. Proposed System and Theoretical Analysis

The proposed single-phase ORC AC/DC converter configuration is established for the UAV WPT implementations as shown in Fig. 1. The new advanced topology provides energy conversion straight from grid to the UAV battery load without requiring a grid side regulator. The presented structure comprises a single filter inductor, asymmetrical connected half-bridge active switches, series-series resonant tuning, a pair of coupling coils, full-bridge rectifier, output filter capacitor and inductor, and the load. The 60 Hz constant frequency and 1 MHz operating frequency are superimposed through GaN half-bridge switches and power conversion from low frequency to high frequency is achieved at the output of ORC. The receiver side superimposed low and high frequency components are rectified to dc and applied to the UAV battery load.

The input grid phase to ground voltage v_{ac} of the presented WPT structure can be constituted by the source phase voltage rms value in time domain as,

$$v_{ac}(t) = \sqrt{2}V_{ac,rms}sin(2\pi f_{60}t) \quad (1)$$

where f_{60} is the 60 Hz grid frequency. The circuit phase current i_{ac} can be expressed using the input current rms value in time domain considering the proposed converter can operate at unity power factor,

$$i_{ac}(t) = \sqrt{2}I_{ac,rms}sin(2\pi f_{60}t) \quad (2)$$

The decoupling capacitors of the system should be selected at the highest load power condition to obtain the unity power factor at the lowest load resistance conditions. The structure input power p_{ac} can be determined by the energy charge and energy discharge of the decoupling capacitors within a cycle operating frequency as,

$$p_{ac}(t) = \frac{1}{2}C_D\left(\sqrt{2}V_{ac,rms}sin(2\pi f_{60}t)\right)^2 f_{sw} \quad (3)$$

where f_{sw} is the operating frequency of the converter. The input phase power can be written by the multiplication of the phase voltage amplitude V_{AC} ($=V_{ac,rms}$) and the decoupling capacitor values C_D ($=C_u=C_d$) as,

$$p_{in}(t) = p_{ac}(t) = C_D V_{AC}^2\left[sin^2(2\pi f_{60}t)\right]f_{sw} \quad (4)$$

The average input power can be calculated with the balanced unity system as,

$$P_{in} = \frac{1}{2}C_D V_{AC}^2 f_{sw} \quad (5)$$

Since the output power P_O and input voltage V_{AC} are known, the decoupling capacitor C_D value can be found as,

$$C_D = \frac{2P_O}{V_{AC}^2 f_{sw}\eta} \quad (6)$$

where η is the efficiency of the proposed system. The system inductor value L_i should be considerably smaller than the proposed topology's input impedance at f_{60} of 60 Hz. Since the input impedance is considered to be a resistive load at the maximum output power, the system can achieve unity power factor characteristic. The unity power factor of the system can be achieved at the minimum output load and the input inductor of L_i can be extracted as,

$$L_i \ll \frac{V_{AC}^2\eta}{2\pi f_{60}P_O} \quad (7)$$

The proposed single-phase WPT system can be reflected with the resonant tank as in Fig. 2 where the input voltage source V_P, resonant capacitors C_P and C_S, two coupled inductors L_P and L_S with equivalent series resistances R_P and R_S, respectively and the load resistance R_L. The input voltage v_P can be expressed by,

$$v_P(t) = \frac{2}{\pi}V_{ac,rms}sin(2\pi f_{60}t)\sum_{n=1,3,..}^{\infty}\frac{1}{n}sin(n2\pi f_{sw}t) \quad (8)$$

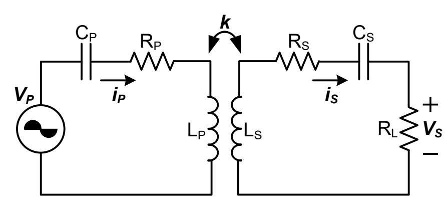


Fig. 2. The presented structure equivalence.

The input voltage magnitude V_P and the primary current I_P can be written by,

$$V_P = \frac{2}{\pi\sqrt{2}}V_{AC}, \quad I_P = \frac{\pi\sqrt{2}}{2}\frac{P_O}{\eta V_{AC}} \quad (9)$$

As seen from Fig. 2, k is the coupling factor between couplers such that the magnetizing inductance L_M and leakage inductance L_L values can be evaluated as,

$$L_M = k\sqrt{L_P L_S} = kL \tag{10}$$

$$L_L = L - L_M = (1-k)L \tag{11}$$

where, both coils L_P and L_S are assumed to be identical. The primary impedance Z_P and secondary impedance Z_S can be described as,

$$Z_P = \frac{1}{j(2\pi f_{sw})C_P} + j(2\pi f_{sw})L_L + R_P \tag{12}$$

$$Z_S = j(2\pi f_{sw})L_L + \frac{1}{j(2\pi f_{sw})C_S} + R_S \tag{13}$$

where Z_M is the magnetizing inductance by $Z_M = j(2\pi f_{sw})L_M$. The secondary side load resistance R_L can be procured as,

$$R_L = \frac{8\,V_O^2}{\pi^2 P_O} \tag{14}$$

In a matrix form equation, the primary and secondary resonant network can be indicated as,

$$\begin{bmatrix} V_P \\ V_S \end{bmatrix} = \begin{bmatrix} Z_P + Z_M & -Z_M \\ -Z_M & Z_M + Z_S + R_L \end{bmatrix} \begin{bmatrix} I_P \\ I_S \end{bmatrix} \tag{15}$$

The proposed topology is switched at the resonant angular frequency ω_R as where, $\omega_R = 1/\sqrt{L_P C_P} = 1/\sqrt{L_S C_S}$. The presented structure voltage gain function $|M_V|$ and current gain function $|M_I|$ can be extracted as,

$$|M_V| = \left|\frac{V_S}{V_P}\right| = \left|\frac{Z_P}{R_L} + \frac{Z_S(Z_P + Z_M)}{R_L Z_M} + \frac{Z_P + Z_M}{Z_M}\right|^{-1} \tag{16}$$

$$|M_I| = \left|\frac{I_S}{I_P}\right| = \left|\frac{Z_M}{Z_M + Z_S + R_L}\right| \tag{17}$$

III. Experimental Results of The Presented Topology

The presented ORC system is built to test for experimental operation from grid to UAV battery load at 1 kW, 110 $V_{AC,RMS}$ input, and 40 V_{DC} output voltages. The proposed system's active and passive components from the input filter and ORC converter, *series-series* resonant compensation with the couplers to the rectifier and output filter are designed and developed as presented in Fig. 3. The designed laboratory prototype of the ORC converter system is shown in Fig. 4. The inverter is built by using GSP65R25HB GaN Insulated-Metal-Substrate (IMS)-based power module with the assembled input filter inductor, the decoupling capacitors, and the gate drivers. Also, two fans with heatsinks are used as the cooling system of the power modules. The inverter's power modules are driven by an HP33120A function generator as the PWM source.

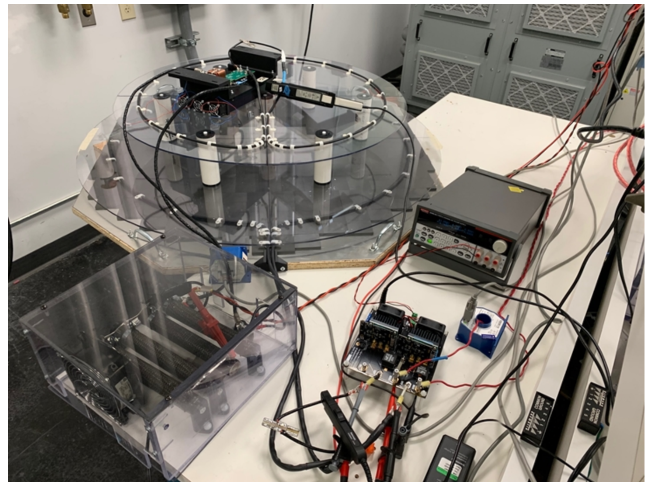


Fig. 3. The designed hardware system from ORC converter through transmitter and receiver coupler coils with series-series resonant compensation system to the full-bridge rectifier and ohmic load.

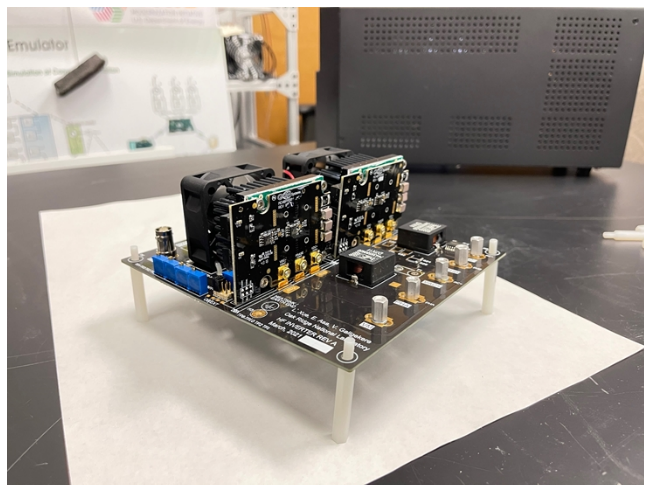
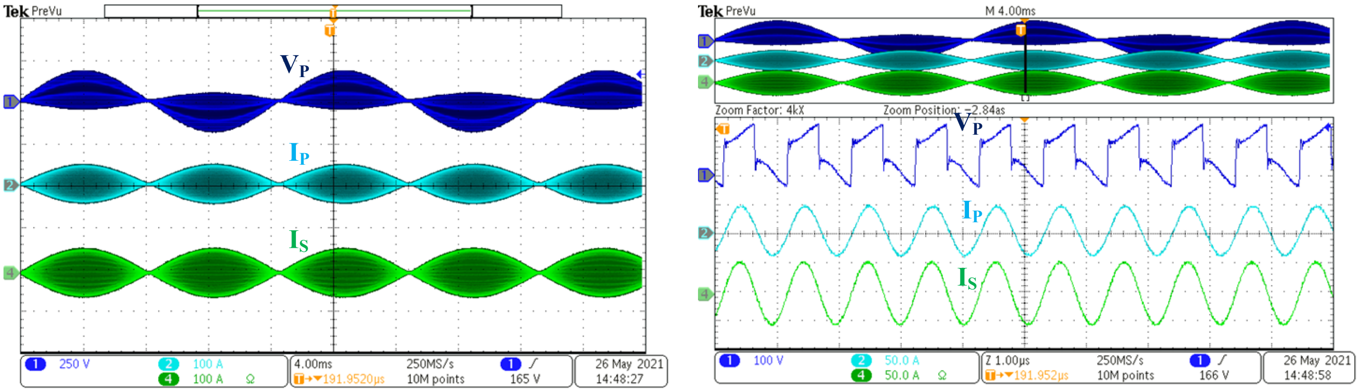


Fig. 4. The designed 1 kW ORC converter.



L_o	output filter inductor	1.5 µH
f_{60}	grid frequency	60 Hz
f_{SW}	operating frequency	1 MHz
t_{dead}	dead time	50 ns

(a) (b)

Fig. 5. Experimental test results of the proposed system: a) the resonant input voltage V_P (250 V/div) and transmitter resonant current i_P (100 A/div), and receiver resonant current i_S (100 A/div) waveforms for [t: 4ms/div, and b) in zoomed view [t: 1 div/1µs

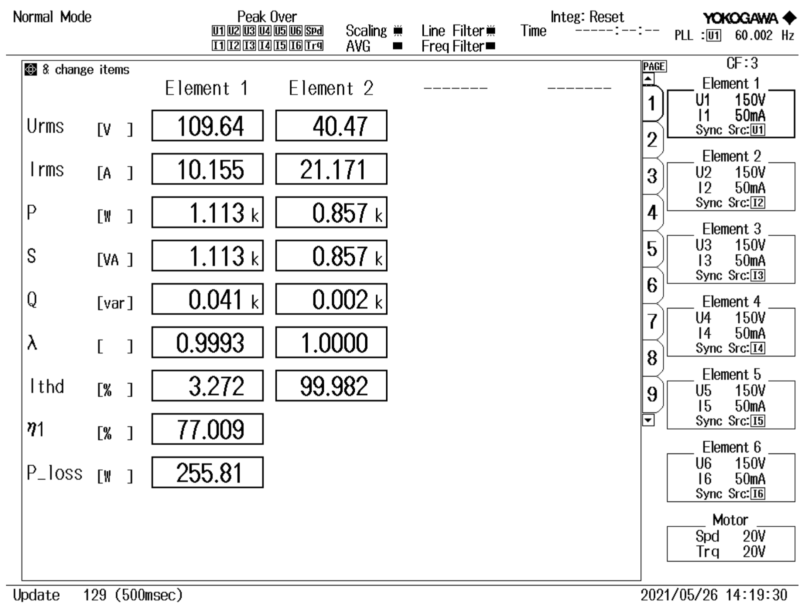


Fig. 6. Input and output power analyzer results of the proposed system.

Furthermore, the couplers are designed for 0.15 coupling factor at 6 inches of air gap. The single-turn primary and secondary coils are made with AWG44 strand based Litz wire with 1.5 ft and 1.2 ft radius, respectively. The primary core is made with Ferroxcube 3F4 ferrite plates. The system parameters of the presented architecture are provided in Table I.

The 1 MHz switching frequency of the proposed converter with 60 Hz envelope frequency are shown in Fig. 5 (a). In this formation, the single-phase line frequency is combined with the high frequency component and delivered through the resonant network and coupler coils and transferred to the secondary side by the proposed ORC. The secondary side voltage is then rectified through the full bridge diodes, output capacitor, and filter inductor to the dc load. The zoomed-in views of the selected waveforms of Fig. 5 (a) are presented in Fig. 5 (b). The topology operates with 50% duty cycle in open loop that the primary active switches switch at zero voltage (ZVS) through the operation in both negative and positive cycles as seen from the waveforms. Also, the coupler currents in transmitter and receiver side coils are pure sinusoidal as seen from the waveforms. Tektronix GHz high-definition oscilloscope is used for data collection in this testing configuration. The numerical measurements of the experimental results are presented in Fig. 6. As seen from the numerical results, the system input phase current THD is acquired around 3.3% with 0.99 power factor. The system input voltage and current waveforms are purely sinusoidal and synchronized with the lowest reactive power around 41 VAr. The system input and output voltages are 110 $V_{AC,RMS}$ and 40 V_{DC}, respectively. The overall efficiency of the system from the input ac source to the output load terminals is 77%. The system numerical values are stored from Yokogawa WT1806E precision power analyzer.

IV. Conclusions

A 1 MHz operating frequency AC/DC ORC converter system is demonstrated for WPT based UAV charging systems in this study. As shown in the results, the presented topology can eliminate active front-end rectifier with PFC which is engaged in regular chargers ensuring grid side maximum THD and minimum PF levels are achieved with minimum number of design stages and active / passive components. The theoretical analysis of the proposed system is performed by mathematical design calculations from the front filter to the resonant circuits and single coupler coils to the load. The system experimental results confirm that the proposed system can achieve the target power. The resonant input voltage and the transmitter and receiver resonant circuit current waveforms are demonstrated with hybrid grid 60 Hz and 1 MHz frequencies. The single phase system power with the voltage amplitude of 110 $V_{AC,RMS}$ is transferred to the secondary output load at 40 V_{DC}. The target power rating of 1kW is achieved 1 kW achieving 77% overall efficiency, 3.3% THD and 0.99PF on the grid side.

Acknowledgements

This project is funded by Oak Ridge National Laboratory's Technology Innovation Program (TIP) under Technology Transfer Office with the project ID UTB2107(6) and name “Operation Duration Extender for Unmanned Aerial Vehicles (UAV)”. This research used resources available at the Power Electronics and Electric Machinery Research Center located at the National Transportation Research Center, a DOE EERE User Facility operated by the Oak Ridge National Laboratory (ORNL). The authors would like to thank the Technology Transfer Office Director, Michael Paulus for his support of this work and his guidance.

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